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Monroe Reservoir, Indiana, Part I: Hydrologic Circulation, Sedimentation, And Water Chemistry

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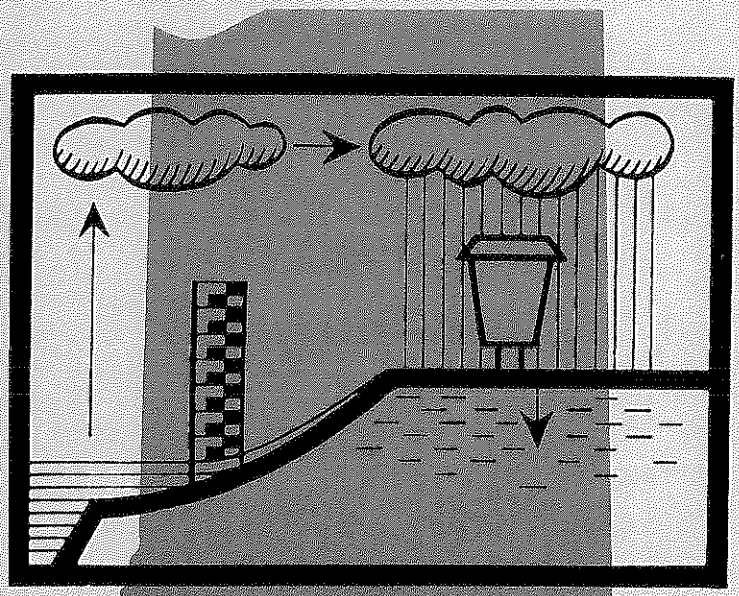
TECHNICAL REPORT No. 87

MONROE RESERVOIR, INDIANA

Part I: Hydrologic Circulation, Sedimentation, and Water Chemistry

Part II: Nutrient Relations



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Part II: W. Y. B. Chang
D. G. Frey

March 1, 1977

INDIANA UNIVERSITY
WATER RESOURCES RESEARCH CENTER
in cooperation with
PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
WEST LAFAYETTE, INDIANA

MONROE RESERVOIR, INDIANA

Part I: Hydrologic Circulation, Sedimentation, and Water Chemistry

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Technical Report No. 87

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March 1977

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Part I

HYDROLOGIC CIRCULATION, SEDIMENTATION, AND WATER CHEMISTRY, MONROE RESERVOIR, INDIANA

K. R. Bradbury, M. J. Graham, and R. V. Ruhe

INTRODUCTION

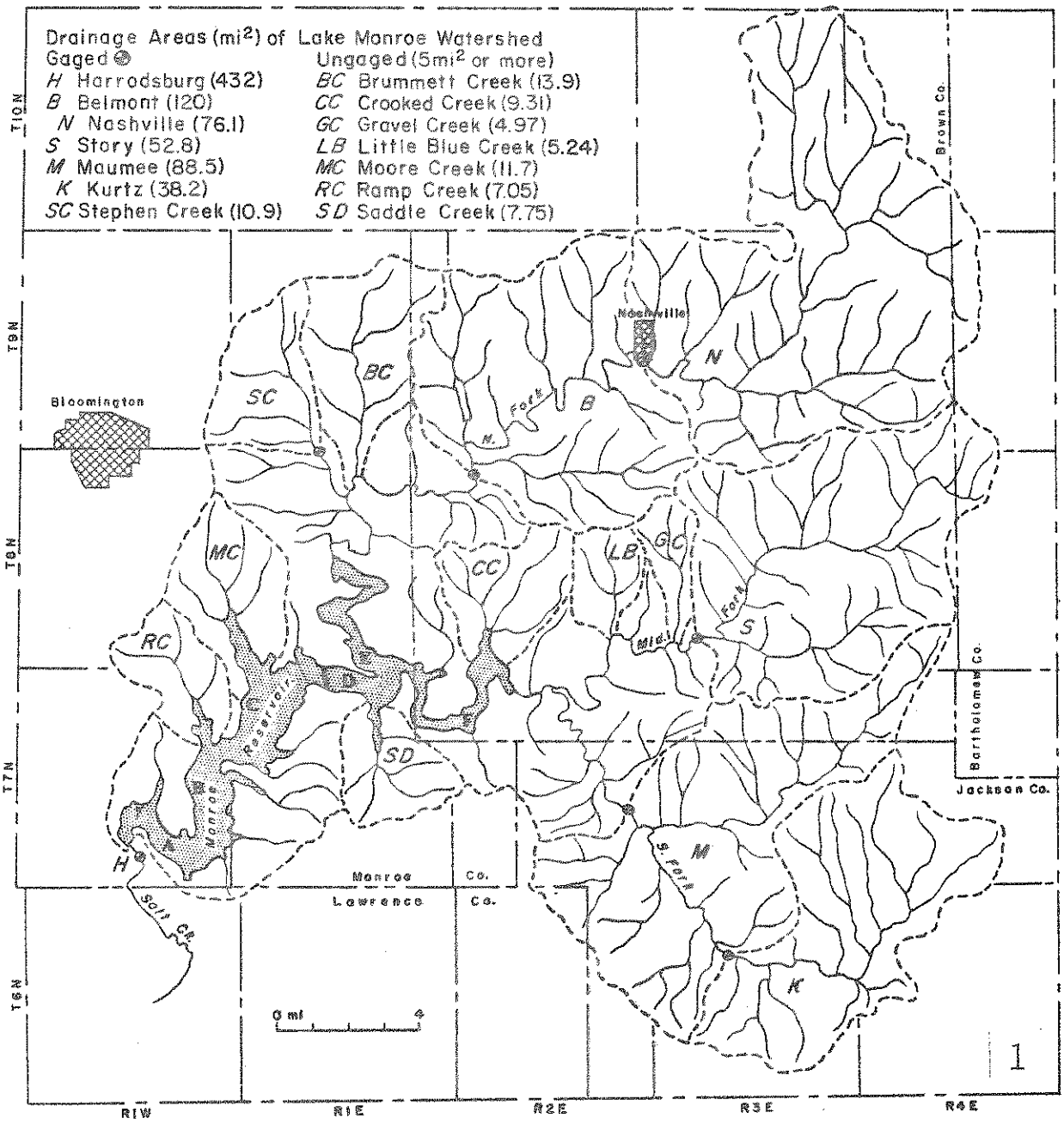
This project began on January 1, 1975 with a scheduled duration of 2 years to December 31, 1976. This study relates the hydrologic circulation pattern of the lake with biological, chemical, and sedimentation characteristics. Results and conclusions are reported herein within the qualification of one unusually dry year during the 2-year study.

Study Area

The dam site of Monroe Reservoir is about 10 miles south of Bloomington, Indiana, on Salt Creek. The watershed above the dam has 432 sq mi and lies dominantly in parts of Monroe, Brown, and Jackson Counties with only minor peripheral areas in Bartholomew and Lawrence Counties (Fig. 1). The waters of Lake Monroe cover 16.8 sq mi at the low-flow regulation pool level of 538 ft above sea level.

The reservoir watershed is on Mississippian age bedrock, and the Borden Group of siltstone, sandstone, and shale underlies most of the drainage basin (Wier and Gray, 1961). The Harrodsburg and Salem Limestones are along the western perimeter, and glacial drift of Pleistocene (Illinoian) age is along the eastern perimeter of the watershed. A few feet of Pleistocene (Wisconsinan) loess mantle the summits of hills.

Fig. 1. Watershed of Monroe Reservoir, Indiana. Subwatersheds identified and labeled by letter. See legend. Areas given in sq mi. Segments of lake labeled A ... F. A and B are lower basin; C is middle basin; D is upper basin; E is inlet of North Fork and F is inlet of Middle and South Forks, Salt Creek. Causeway is black line below D. Gaging stations are Harrodsburg (H), Stephens Creek (SC), Belmont (B), Nashville (N), Story (S), Maumee (M), and Kurtz (K).


Drainage Areas (mi²) of Lake Monroe Watershed
Gaged
H Harrodsburg (432)
B Belmont (120)
N Nashville (76.1)
S Story (52.8)
M Maumee (88.5)
K Kurtz (38.2)
SC Stephen Creek (10.9)
Ungaged (5mi² or more)
BC Brummett Creek (13.9)
CC Crooked Creek (9.31)
GC Gravel Creek (4.97)
LB Little Blue Creek (5.24)
MC Moore Creek (11.7)
RC Ramp Creek (7.05)
SD Saddle Creek (7.75)
T10N
T9N
T8N
T7N
T6N
R1W
R1E
R2E
R3E
R4E
Bloomington
Nashville
Brown Co.
Bartholomew Co.
Jackson Co.
Monroe Co.
Lawrence Co.
Monroe Reservoir
Salt Cr.
0 mi
4
1

The dominant soils in the watershed relate to the surficial materials and bedrock (Fig. 2). Wakeland, Stendel, Haymond, and Bartle soils are on the alluvial deposits of Salt Creek and its tributaries. Dominant upland soils are Wellston and Zanesville which are formed in thin loess and weathered Borden rocks, and Berks, Gilpin, and Weikert soils which are formed in the weathered siltstone, sandstone, and shale. In the limestone area Crider soils are in thin loess and weathered limestone, and Hagerstown, Frederick, and Corydon soils are formed in weathered limestone. In the area of glacial drift, Cincinnati and Rossmoyne soils are formed in thin loess and weathered glacial till, and Hickory soils are in the weathered till (Purdue Univ., 1971).

Using a statistical land-use sample from the 100 sq mi area around the lake in the reservoir watershed, more than half the area is under forest dominated by oak, maple, and beach (Chiesa and others, 1975). Among agricultural and other uses, each type is <10% of the area.

The upland is thoroughly dissected by a well-integrated drainage net. In the sample area almost 70% of the hillslopes have gradients >20%. The maximum local relief is about 185 ft (Chiesa and others, 1975).

Objectives

Five objectives were originally defined, and the first three relate to the physical-chemical system of Monroe Reservoir:

(1) To determine the hydrologic circulation of the reservoir as it relates to sedimentation and water-chemistry systems.

Fig. 2. Soil Associations, Monroe Watershed:

3. Wakeland-Stendal-Haymond-Bartle: Nearly level, somewhat poorly drained, silty Wakeland and Stendal and well drained, silty Haymond in alluvial deposits, and somewhat poorly drained, silty Bartle with fragipans in acid alluvial deposits.

9. Haymond-Wakeland: Nearly level, well drained, silty Haymond and somewhat poorly drained, silty Wakeland in alluvial deposits.

92. Cincinnati-Hickory: Sloping, well drained, silty Cincinnati with fragipans in wind-blown silts and weathered glacial till, and steep, well drained, loamy Hickory in weathered till.

93. Cincinnati-Rossmoyne-Hickory: Sloping, well drained, silty Cincinnati and moderately well drained, silty Rossmoyne, both with fragipans, in wind-blown silts and weathered glacial till, and steep, well drained, loamy Hickory in weathered till.

95. Cincinnati-Ava: Sloping, well drained, silty Cincinnati and moderately well drained, silty Ava, both with fragipans, in wind-blown silts and weathered glacial till.

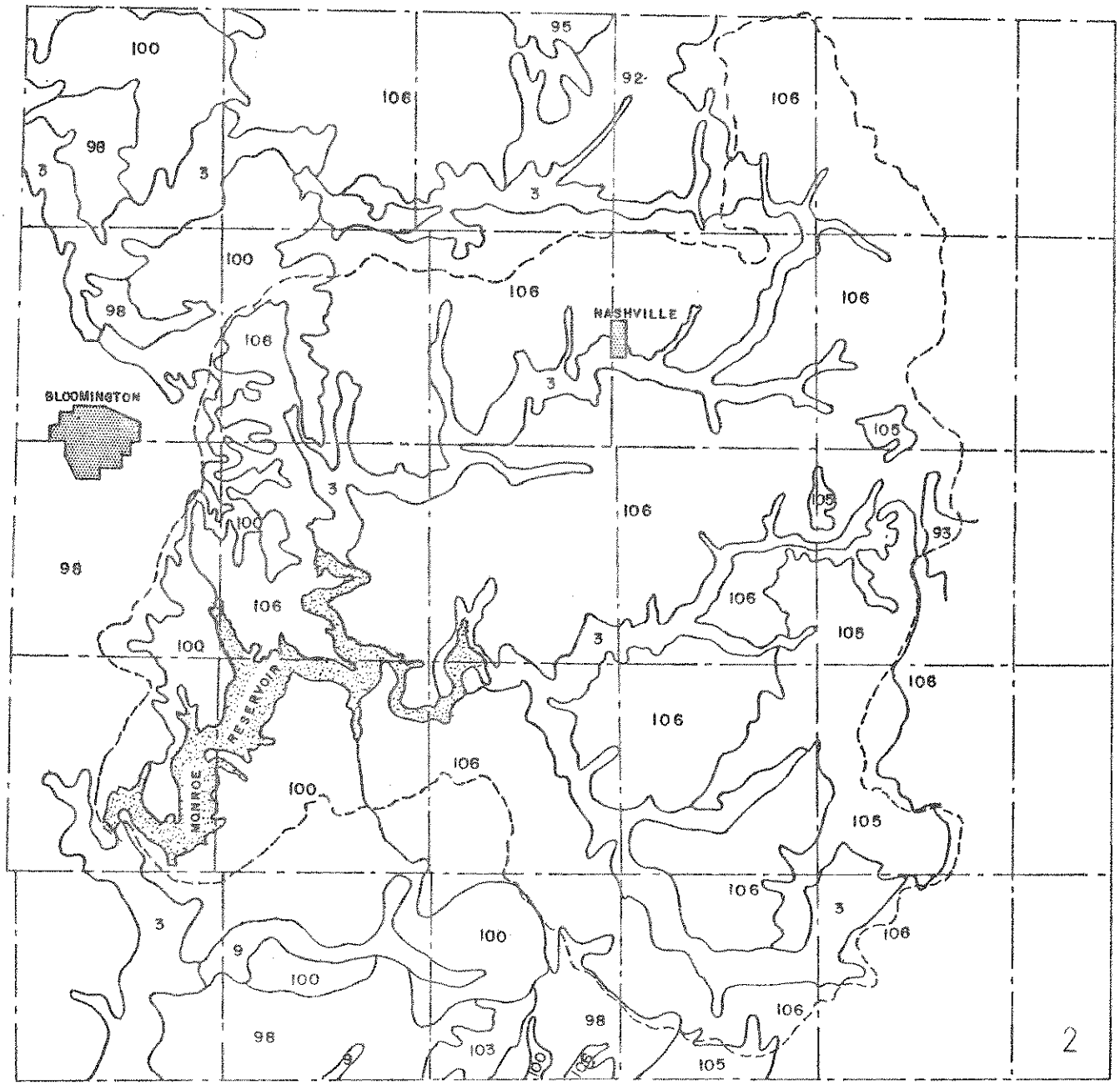
98. Crider-Hagerstown-Frederick: Sloping, well drained, silty Crider in wind-blown silts and weathered limestone and clayey Hagerstown and Frederick in weathered limestone.

100. Corydon-Weikert-Berks: Steep, well drained, shallow, clayey Corydon in weathered limestone, and steep, well drained, shallow, loamy Weikert and moderately deep, loamy Berks in weathered sandstone and shale.

105. Wellston-Zanesville-Berks: Sloping, well drained, silty Wellston and sloping, well drained, silty Zanesville with fragipans, both in wind-blown silts and weathered sandstone and shale, and steep Berks in weathered sandstone and shale.

106. Berks-Gilpin-Weikert: Steep, well drained, loamy Berks and Gilpin and shallow, loamy Weikert in weathered sandstone and shale.

From Purdue University (1971).


100
95
92
106
98
3
NASHVILLE
BLOOMINGTON
105
93
MONROE RESERVOIR
103
2

(2) To develop baseline data for sedimentation and water quality in the reservoir.

(3) To determine the nutrient inputs to the reservoir from North, Middle, and South Forks of Salt Creek.

The last two objectives involve the limnology of the reservoir.

(4) To determine the importance of rooted macrophytes in the mixing basin above the causeway as "nutrient scrubbers," thereby protecting the basin below the causeway from excessive blooms of algae.

(5) To determine the annual cycle of phytoplankton in the reservoir both above and below the causeway, supplemented by in situ measurements of photosynthesis with ^{14}C and laboratory studies on nutrient limitations at various seasons.

HYDROLOGIC CIRCULATION

The circulation system of the reservoir is being studied through two approaches: (1) the mass inflow-outflow system, and (2) local systems within the upper, middle, and lower basins of the reservoir (Fig. 1).

Stream Inflow

Inflow to the reservoir is measured at 4 stream gages: Stephens Creek, Belmont, Story, and Maumee (Fig. 1). Stephens Creek gage is a U. S. Geological Survey facility. The other gages were installed by project personnel. The Belmont gage was reactivated and calibrated by project personnel. Two subsidiary gages are at Nashville and Kurtz. The gages continue to be rated on stream. A total area of 272 sq mi is gaged. Stream gaging follows standard procedures (Carter and Davidian, 1968; Buchanan and Somers, 1968, 1969).

On the basis of discharge per hydrologic event through mid-year 1976, the gages have been related by discharge through the gage and drainage area above the gage. A hydrologic event is a hydrograph separation where the rising and recessional limbs comprise an event. Belmont Watershed has the largest gaged drainage area of 120 sq mi, and Stephens Creek has the smallest gaged drainage area of 10.9 sq mi. The drainage area of other gaged watersheds are within this size range. Using Belmont Watershed with largest area as a base for comparison, discharge (cfs) through the other gages relates to discharge (cfs) through the Belmont gage per hydrologic event as:

Stephens Creek to Belmont (10.9 to 120 sq mi):

$Y = 31.964 + 0.10X$; $r = 0.94$; $R^2 = 0.88$; $Se = 55.6$ cfs

Kurtz to Belmont (38.2 to 120 sq mi):

$Y = 121.92 + 0.276X$; $r = 0.91$; $R^2 = 0.83$; $Se = 419$ cfs

Story to Belmont (52.8 to 120 sq mi):

$Y = -129.05 + 0.582X$; $r = 0.96$; $R^2 = 0.93$; $Se = 235$ cfs

Nashville to Belmont (76.1 to 120 sq mi):

$Y = -459.33 + 0.936X$; $r = 0.98$; $R^2 = 0.96$; $Se = 315$ cfs

where r is the coefficient of correlation, R^2 is the coefficient of determination or the proportion of the total variance in Y explained by the regression, and Se is the standard error. Within the range of standard error, 83 to 96% of the variance is explained by the regressions.

The Maumee gage (drainage area of 89 sq mi) does not relate to the Belmont gage within the systematic discharge-drainage area model of the other gages. Among the other 4 gages the b constant in the regression $Y = a + bX$ increases as the size of the drainage area increases. The Maumee gage is affected by backwater from the lake

which produces anomalously high stages at the gage when lake levels are high. The backwater effects were not apparent until low-flow conditions began and continued many months through the unusually dry period during the study. Consequently, methods for correction for backwater effects could not be used (Corbett, 1943), so the following procedure was used.

Low-flow stages at Maumee gage (discharge range of 10 - 100 cfs) are plotted against lake stages and are essentially the same value (Fig. 3, horizontal broken line) as the lake stage varies from 536 to 538 ft. When lake stage is 538.1 ft, the stage at Maumee gage varies from 1.5 ft local datum to 3.7 ft with one value at 4.8 ft (Fig. 3, vertical broken line). The vertical offset in stage at the Maumee gage shows the backwater effect. However, when lake stage is above 538.1 ft, the stage at Maumee gage rises with an almost 1:1 relation to rise in lake stage (Fig. 3, solid regression line). This almost equal rise in stage is direct evidence of backwater effects at the gage. Consequently, a correction for lake backwater can be made at the Maumee gage. The difference between lake stage above-538.1 ft and 538.1 ft (e.g., 540.1 - 538.1 = 2.0 ft) is subtracted from the stage recorded at Maumee gage to give a corrected stage at the gage (e.g., 10.2 - 2.0 = 8.2 ft local datum). A rating curve of stage-discharge is prepared using the corrected stage values. Instantaneous and mean daily discharges then are calculated from the corrected rating curve. As a result, discharge through Maumee gage is reduced about 10% at times of high-lake stage in comparison to calculated discharges if backwater effects are ignored.

The relation of discharge to size of drainage area can be modeled within the limits given above. The regressions may be scaled to a common point of origin and the b values are plotted against the percentage of area of a smaller to larger watershed (Fig. 2). The b value is the constant in the general form of the equation $Y = a + bX$, or in simple terms, the slope of the regression line. For example, the b value in the Stephens Creek-Belmont regression is 0.1, and the area of Stephens Creek Watershed is 9.1% of the area of the Belmont Watershed.

Returning to the discharge-drainage area relations previously described, regression equations also may be developed for total monthly discharges for smaller watersheds, Stephens Creek, Kurtz, Story, and Nashville, versus the large Belmont Watershed. In addition, the Beanblossom Watershed (14.6 sq mi), gaged by the U. S. Geological Survey at Beanblossom in Brown County is used. This small watershed is north of Nashville and just across the divide of the Salt Creek Watershed. Total monthly discharge (Y in cfs) for the smaller watersheds relates to corresponding discharge at Belmont (X) as:

Stephens Creek to Belmont (10.9 to 120 sq mi)

$Y = 1.88 + 0.08X$; $r = 0.99$; $Se = 1.79$ cfs

Beanblossom to Belmont (14.6 to 120 sq mi)

$Y = 21.97 + 0.12X$; $r = 0.99$; $Se = 41.6$ cfs

Kurtz to Belmont (38.2 to 120 sq mi)

$Y = 168.0 + 0.28X$; $r = 0.96$; $Se = 390$ cfs

Story to Belmont (52.8 to 120 sq mi)

$Y = 329.2 + 0.54X$; $r = 0.97$; $Se = 380$ cfs

Nashville to Belmont (76.1 to 120 sq mi)

$Y = 25.34 + 0.57X$; $r = 0.99$; $Se = 118$ cfs

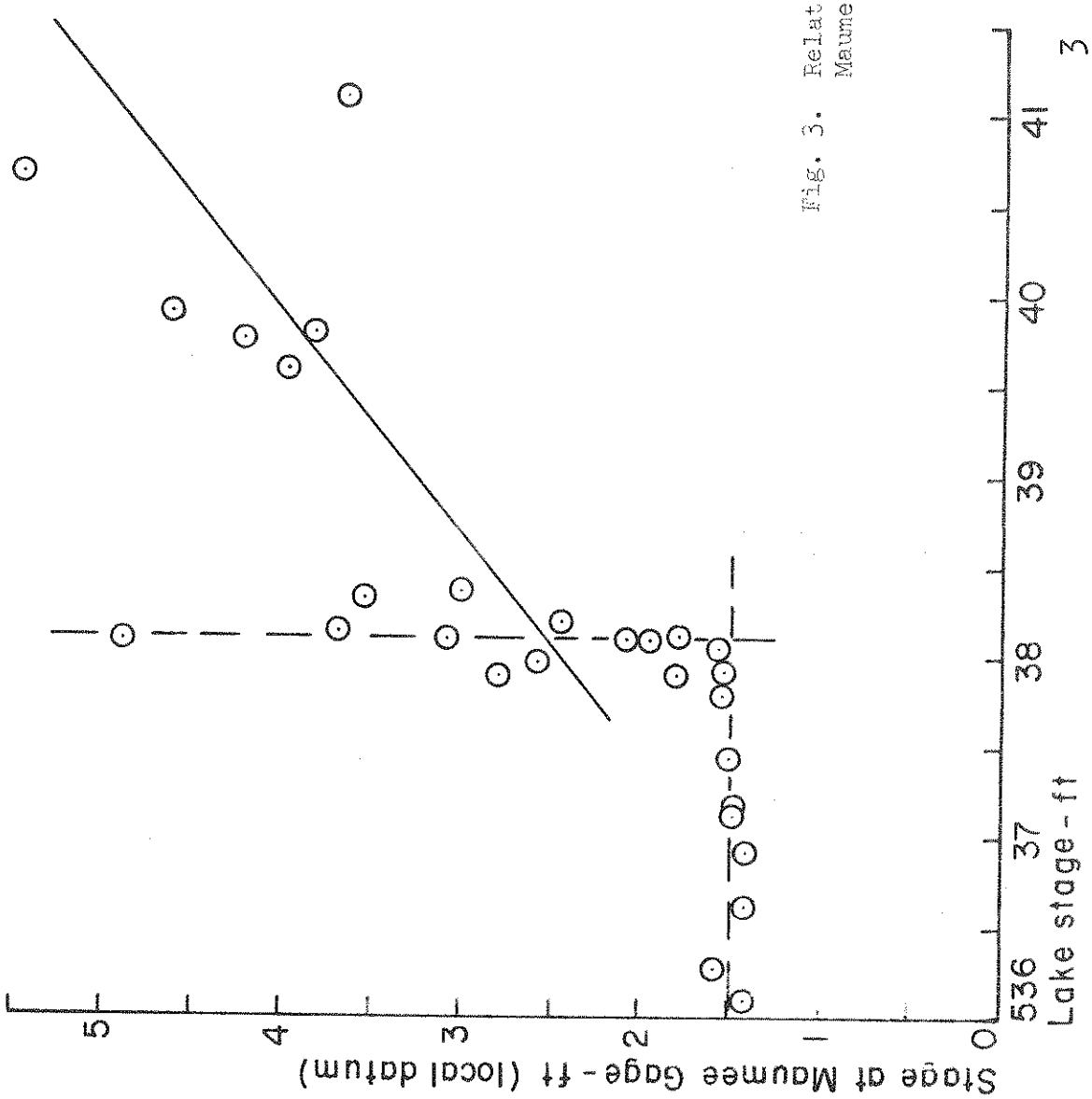


Fig. 3. Relation of stream stage at Maumee gage to lake stage.

The b constants x 100 in these equations are the percent of total monthly discharges from the smaller watersheds relative to total monthly discharges from Belmont Watershed. The b constants then may be plotted (Fig. 4) against the area of each smaller watershed expressed as a percentage of the Belmont Watershed, and a regression may be calculated for the best line of fit as:

$$Y = 0.002 + 0.0097X;\ r = 0.97;\ Se = 0.06$$

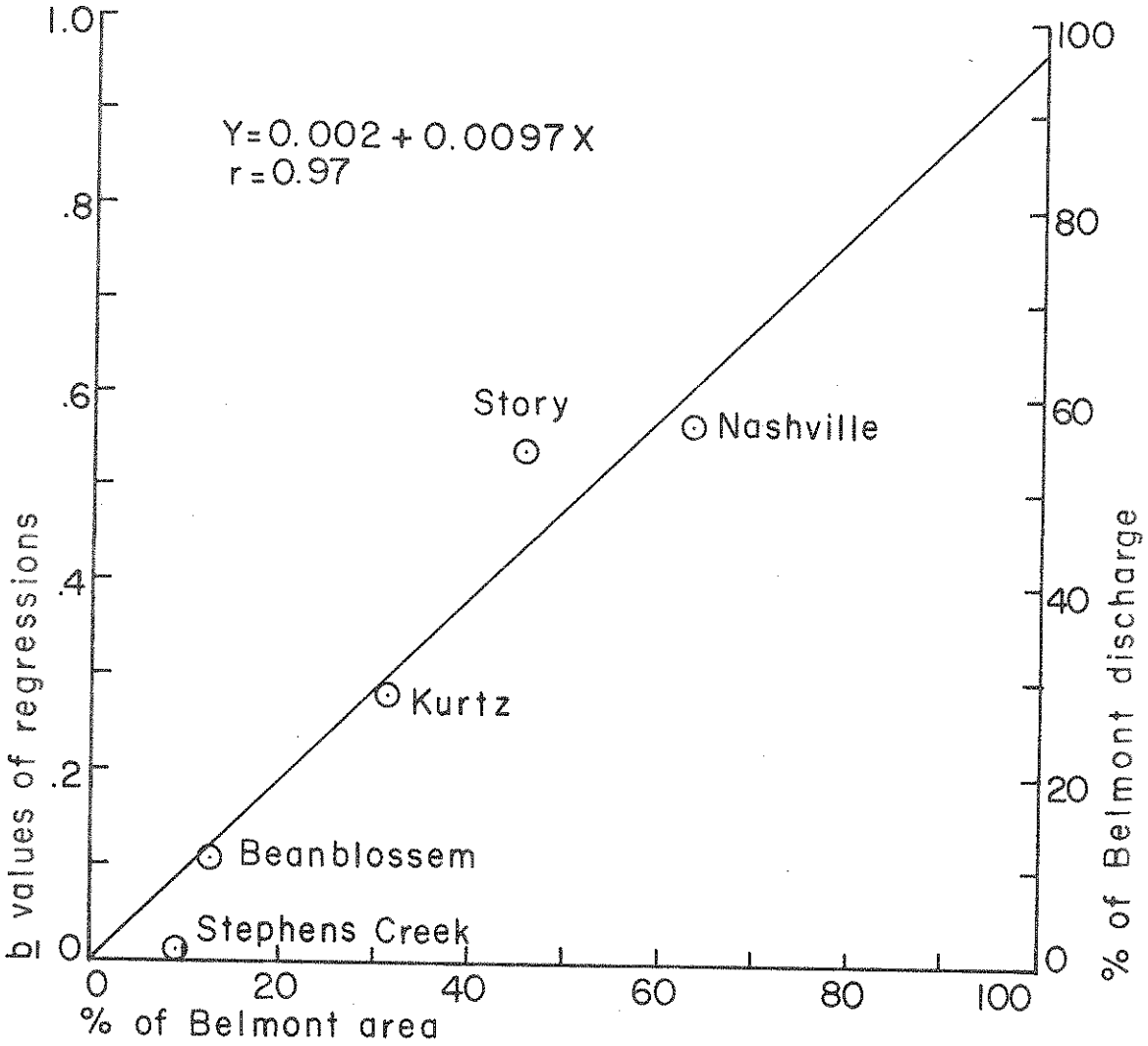
An estimate of discharge may be made for any watershed (X) whose area is known as a percentage of area of the Belmont Watershed. Solving for Y (x 100) gives the discharge of the watershed expressed as a percentage of Belmont discharge. This technique is used to estimate discharge for ungaged watersheds that total 143 sq mi in the reservoir drainage basin.

To estimate the discharge from the ungaged areas, small watersheds were grouped by size of drainage areas: (A) 5 to 15, (B) 1 to 5, and (C) 1 sq mi. In group A are 6 watersheds that total 47.2 sq mi with an average size of 7.9 sq mi which is 6.5% of the Belmont area. Using the estimate equation, the estimated discharge is 6.5% of Belmont discharge for the average size watershed. For the 6 watersheds the total estimate is 39% of Belmont discharge.

In group B are 17 watersheds that total 44 sq mi with an average size of 2.6 sq mi which is 2.1% of the Belmont area. The estimated discharge for the average size watershed is 2.2% of Belmont discharge, and the total is 37.4% of Belmont discharge.

In group C are 52 watersheds that total 52 sq mi with an average size of 1 sq mi or 0.8% of the Belmont area. Estimated discharge is 1% of Belmont discharge, and the total is 52% of Belmont discharge. The sum for the 3 groups is 128% of Belmont discharge. Thus, the

Fig. 4. Nomograph for estimation of runoff from ungaged watersheds. Total monthly discharges from Stephens Creek, Beanblossom, Kurtz, Story, and Nashville Watersheds are related to total monthly discharge from Belmont Watershed by regressions of general form $Y = a + bX$. The $\underline{b}$ values of the individual regressions are plotted against the area of each watershed expressed as a percentage of Belmont area. The regression of these relations is a straight line with almost a 1:1 slope. A direct discharge-area relation is established. To predict discharge from an ungaged part of the Monroe Watershed, calculate its area (A) expressed as a percentage of Belmont area. The discharge is then 0.97A which is expressed as a percentage of Belmont discharge.


Y=0.002+0.0097X
r=0.97
Story
Nashville
Kurtz
Beanblossem
Stephens Creek
b values of regressions
% of Belmont area
% of Belmont discharge
1.0
.8
.6
.4
.2
0
0
20
40
60
80
100
100
80
60
40
20
0

4

estimate for total monthly discharge from the ungaged areas is Belmont discharge times the factor 1.28.

The major hydrologic circulation system of the reservoir is modeled using:

$$\text{Inflow} = \text{Outflow} \pm \text{Change in storage}$$

where inflow = runoff to the lake + precipitation on the lake + groundwater flow to the lake; where outflow = discharge at the dam + evaporation from the lake surface + seepage in the basin + water extracted for use in Bloomington; and where storage = change in lake volume + bank storage. Runoff to the lake is measured directly at the Belmont, Story, Maumee, and Stephens Creek gages, and the total gaged area is 272 sq mi or 63% of the reservoir watershed (Fig. 1). Runoff to the lake from the ungaged area of 143 sq mi or 33% of the drainage basin is estimated using the discharge-drainage area technique previously described.

Precipitation

Precipitation is measured in Corps of Engineers rain gages at the reservoir dam and at Nashville and at a U. S. Weather Bureau station at Indiana University in Bloomington (Fig. 1). From July 1975 through July 1976, rainfall by storms related among the gages as:

(a) Dam to Bloomington: $Y = 0.125 + 0.90X$
$r = 0.73$ and $Se = 0.5$ in

(b) Nashville to Bloomington: $Y = 0.08 + 0.69X$
$r = 0.85$ and $Se = 0.27$ in

(c) Dam to Nashville: $Y = 0.16 + 1.07X$
$r = 0.71$ and $Se = 0.55$ in

These weather stations are located as points of a triangle with side (a) west of the reservoir and side (b) north of the reservoir.

The long axis of the reservoir is along side (c). The regression equations express the rainfall gradients along the sides of the triangle, and the last gradient, along the axis of the reservoir, is about 1:1 (b constant 1.07). Consequently, rainfall recorded at the dam is a reasonable estimate for rainfall on the reservoir.

The volume of rainfall on the lake surface is standardized to the surface area of the average stage for a month. The area is determined from the Corps of Engineers stage-area curve (Fig. 5).

Groundwater flow to the reservoir was not measured.

Outflow

Outflow from the reservoir consists of discharge at the dam which is measured at the Harrodsburg gage (Fig. 1, Pl. 1), evaporation from the lake surface, seepage loss, and withdrawal for water supply. The City of Bloomington uses about 30 acre-feet of water daily. Daily records of withdrawal are available from the city and are used in the inflow-outflow model.

Evaporation from the lake surface was estimated using the Penman method (Gray and others, 1973) which is based on an energy budget consisting of temperature, humidity, wind speed, solar radiation, and percentage of sunshine. Volume of water evaporation from the lake surface is standardized to the surface area of the average stage for a month. The nearest first-class weather station where such baseline data are collected is the National Weather Service station at Weir Cook Airport, Indianapolis, Indiana, which is about 60 mi north of Monroe Reservoir. Unfortunately, evaporation pan measurements at the dam were terminated during the year preceding this current study.

Seepage loss was not measured.

Storage of water in the lake was calculated from the stage-capacity curve of the Corps of Engineers (Fig. 5).

Inflow-Outflow-Storage Model

The budget of the model is given in Table 1, and the testing period is from December 1, 1975 to December 31, 1976. Two episodes are tested with one being the wetter part and the second being the whole of the 13-month period. At the beginning of December 1975 the lake stage was 538.2 ft, and at the end of April 1976 the stage was 538.1 ft. During this time, there were numerous events of inflow to the reservoir, and outflow was controlled at the dam as shown at the Harrodsburg gage (Pl. 1, cf. Pl. 2). The algebraic sum of the balance of inflow and outflow has a deficit of 4,400 acre-feet of inflow at the end of the wetter period. The algebraic sum of change in storage capacity has a deficit of 1,100 acre-feet. Thus, 3,300 acre-feet or 1.5% is unaccounted in the budget of about 225,000 total acre-feet.

The average monthly storage capacity in the reservoir during the period was 198,334 acre-feet, and total outflow was 228,000 acre-feet. Assuming total exchange of water in the inflow-outflow system, the water was replaced 1.15 times in 5 months or wholly replaced in 4.3 months.

The spring, summer, and fall of 1976 were unusually dry, and inflow to the reservoir decreased fourfold from March to April and remained low throughout the rest of the year (Table 1). Consequently, there were deficits of inflow as outflow was controlled at the dam.

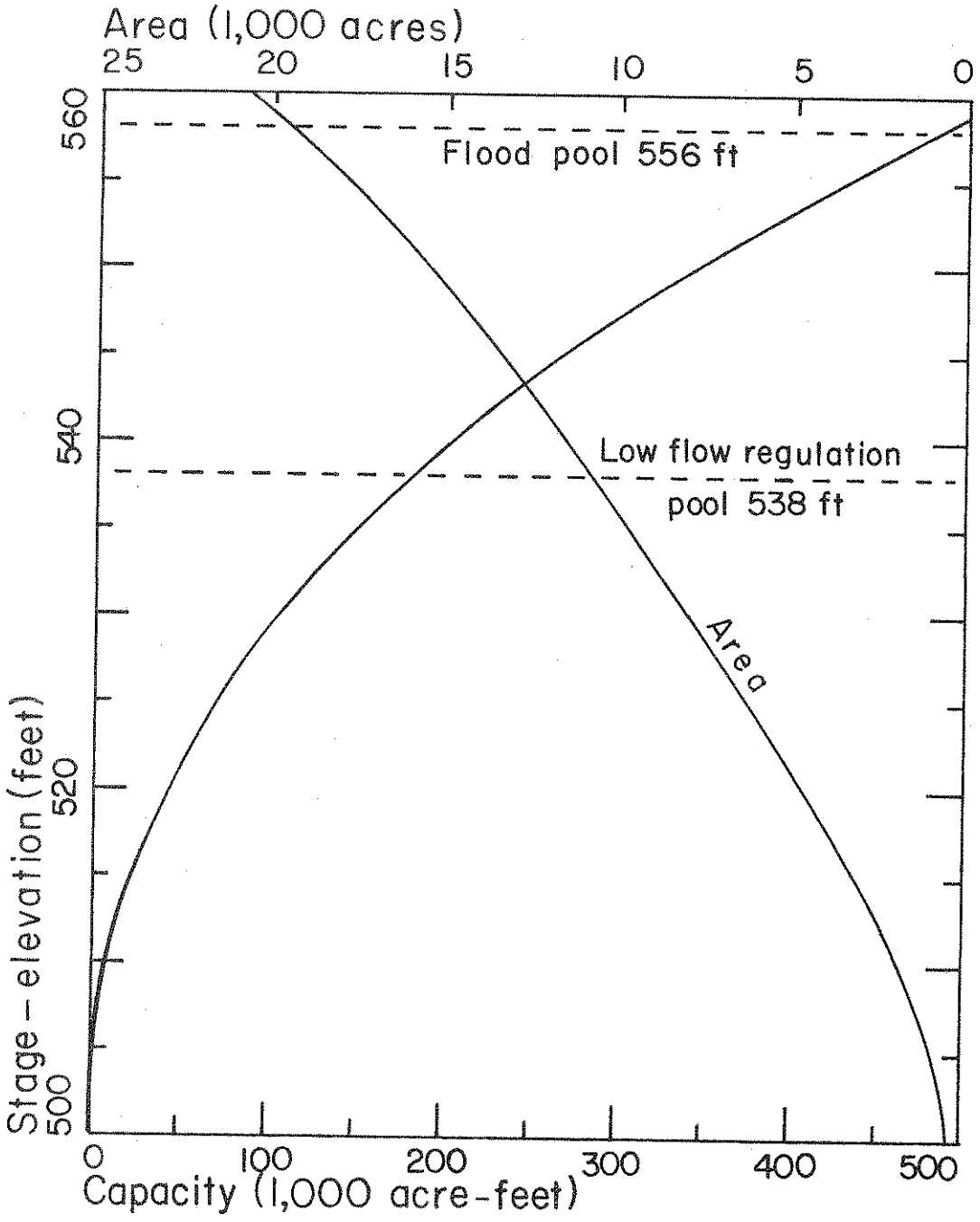
Table 1. Inflow-Outflow-Storage Model, Monroe Reservoir, December 1, 1975 - December 31, 1976
(in acre-feet)

Month	Inflow*	Outflow#	Balance	Algebraic Sum	Stage/Date (ft)	Capacity	Change in Capacity	Algebraic Sum
					538.2/11-30	184,695		
Dec 75	62,000	32,600	29,400		540.5/12-31	210,323	25,600	
Jan 76	57,900	68,000	-10,100	19,300	540.2/ 1-31	206,676	- 3,600	22,000
Feb	47,200	49,600	- 2,400	16,900	540.0/ 2-29	204,199	- 2,500	19,500
Mar	45,500	62,000	-16,500	400	538.4/ 3-31	186,861	-17,300	2,200
Apr	11,000	15,800	- 4,800	- 4,400	538.1/ 4-30	183,611	- 3,300	- 1,100
May	9,400	9,100	300	- 4,100	537.9/ 5-31	181,444	- 2,200	- 3,300
Jun	7,400	10,800	- 3,400	- 7,500	537.9/ 6-30	181,444	0	- 3,300
Jul	6,100	10,500	- 4,400	-11,900	537.6/ 7-31	178,518	- 2,900	- 5,800
Aug	3,000	10,000	- 7,000	-18,900	537.0/ 8-31	171,583	- 6,900	-12,700
Sep	3,700	7,700	- 4,000	-22,900	536.5/ 9-30	166,490	- 5,100	-17,800
Oct	5,900	6,200	- 300	-23,200	536.2/10-31	162,589	- 3,900	-21,700
Nov	3,800	5,100	- 1,300	-24,500	535.8/11-30	159,217	- 3,400	-25,100
Dec	2,000	4,300	- 2,300	-26,800	535.5/12-31	155,329	- 3,900	-28,800
	264,900	291,700	-26,800					

Month	Inflow*				Outflow#			
	Gaged	Ungaged	Rainfall	Total	Dam Discharge	Water Supply	Evaporation	Total
Dec 75	40,600	17,500	3,900	62,000	31,100	900	600	32,600
Jan 76	37,600	17,900	2,400	57,900	66,700	1,000	300	68,000
Feb	28,800	16,300	2,100	47,200	47,200	900	1,500	49,600
Mar	29,200	12,700	3,600	45,500	56,900	900	4,200	62,000
Apr	6,300	3,800	900	11,000	10,000	900	4,900	15,800
May	3,300	2,600	3,500	9,400	3,000	800	5,300	9,100
Jun	3,000	1,900	2,500	7,400	3,000	800	7,000	10,800
Jul	1,400	700	4,000	6,100	3,000	900	6,600	10,500
Aug	700	400	1,900	3,000	3,000	1,000	6,000	10,000
Sep	600	400	2,700	3,700	3,000	900	3,800	7,700
Oct	1,400	900	3,600	5,900	3,000	900	2,300	6,200
Nov	1,600	1,100	1,100	3,800	3,000	800	1,300	5,100
Dec	1,000	600	400	2,000	3,000	800	500	4,300

Fig. 5. Stage-area and stage-capacity curves for Monroe Reservoir. Stage is given as elevation in feet above mean sea level. At the low-flow regulation pool stage of 538 ft, the reservoir capacity is about 182,525 acre-feet, and the lake area is about 10,750 acres or 16.8 sq mi.

From U. S. Army Corps of Engineers.


Area (1,000 acres)
25
20
15
10
5
0
560
540
520
500
Flood pool 556 ft
Low flow regulation
pool 538 ft
Area
Stage - elevation (feet)
0
100
200
300
400
500
Capacity (1,000 acre-feet)

5

Lake stage was progressively lowered below low-flow regulation pool level (538 ft) to 535.5 ft. The change in capacity of the reservoir had a corresponding deficit for each month exclusive of June.

Applying the inflow-outflow-storage budget (Table 1), the algebraic sum of the inflow-outflow system has a deficit of 26,800 acre-feet at the end of the 13-month period. The algebraic sum of change in storage capacity has a deficit of 28,800 acre-feet. Thus, 2,000 acre-feet or <1% are unaccounted in the budget of the waters of the reservoir. The gross circulation model of the reservoir is reasonably accurate.

During the 8-month period with lake stage below the 538-feet level, the total controlled outflow was 63,700 acre-feet and the average monthly capacity was 169,577 acre-feet. About 37.6% of the reservoir was replaced. Assuming total exchange of water in the inflow-outflow system, about 21.3 months would be required to wholly replace the water during low-stage conditions.

Local Circulation

Local circulation is difficult to measure in the reservoir. Currents are not detectable by metering devices. They are measurable by use of drogues. For example, at the causeway that separates the upper and middle basins (Fig. 1), a shear may form under certain wind conditions. With a westerly wind of 3 mph with resultant waves, the surface current velocity is 8.3 ft/min to the east (Fig. 6). The velocity of this directional current decreases to 6.9, 1.5, and 1.3 ft/min at respective depths of 0.5, 5.5, and 9.5 ft. At a depth of 17.5 ft, the current velocity is 3.6 ft/min but toward the west.

Not enough drogue measurements have been made to define the circulation system within the reservoir or its individual basins.

Preliminary results of wave study show that wave height (ft) relates to wind velocity (mph) as:

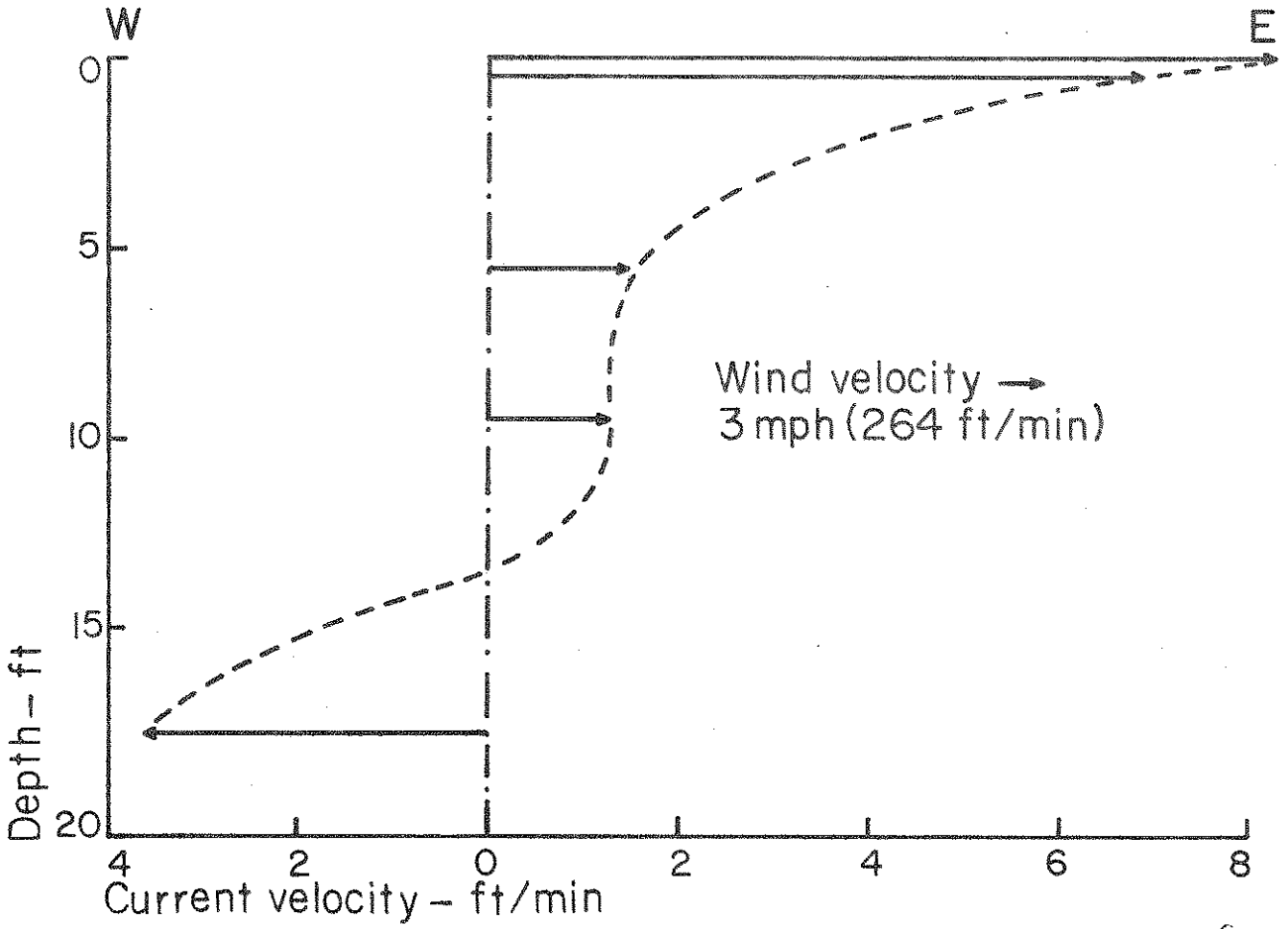
$$Y = 0.06\ e^{0.14X}$$
$$R^2 = 0.79$$

and wave height (ft) relates to fetch (ft) as:

$$Y = 0.319 + 0.115X$$
$$r = 0.90 \text{ and } Se = 0.26 \text{ ft}$$

The circulation system within basins caused by wave generation requires additional study.

Fig. 6. Current shear through causeway with westerly wind 3 mph. Upper layer of water moves eastward from middle to upper basin with a surface-current velocity of >8 ft/min. Eastward current velocity decreases to ∿1 ft/min at depth of ∿10 ft. Current in lower layer of water is westward and downlake from middle to lower basin with a velocity of ∿4 ft/min.


W
E
0
5
10
15
20
Depth – ft
Wind velocity →
3 mph (264 ft/min)
4
2
0
2
4
6
8
Current velocity – ft/min

6

SEDIMENTATION SYSTEM

The sedimentation system is being investigated with a threefold approach: (1) relation of suspended sediment to the inflow-outflow-storage model, (2) comparison of survey-fathometer profiles to original valley topography and previous profiles, and (3) examination and analysis of cores extracted from the lake bottom.

Input-Output Model

The first approach uses the model:

(Sediment input) - (Sediment output) = (Sediment trapped)

Sediment input was measured at the stream gages and was estimated from ungaged areas as in the water balance model. Sediment derived from shoreline erosion is not included, because not enough time was available to study this problem during this phase of the work.

Suspended-sediment samples were collected at the gages at times of instantaneous discharge. The samples were analyzed in the laboratory for turbidity using a Hach Model 2100A Turbidimeter followed by filtering and ashing of the sample. Suspended sediment (mg/l) relates to turbidity (NTU) as:

$$Y = 2.91 + 1.35X$$
$$r = 0.98 \text{ and } Se = 20.9 \text{ mg/l}$$

For each gage instantaneous suspended-sediment discharge was calculated as (Johnson, 1971; Porterfield, 1972):

$$Qsi = 0.0027\ C\ Qwi$$

where Qsi is instantaneous suspended-sediment discharge in tons/day; C is the concentration in mg/l; and Qwi is instantaneous water

discharge in ft^3/sec. Suspended-sediment load at each gage relates to discharge as expressed by an equation of the general form $Y = aX^b$:

Belmont gage (additive):	$Y = 0.02X^{1.11}$,	$r = 0.96$
	$Y = 0.0005X^{2.25}$,	$r = 0.95$
Maumee gage (additive):	$Y = 0.0446X^{0.92}$,	$r = 0.96$
	$Y = 0.0013X^{1.78}$,	$r = 0.93$
Stephens Creek gage:	$Y = 0.0469X^{1.15}$,	$r = 0.84$
Story gage (additive):	$Y = 0.035X^{0.889}$,	$r = 0.96$
	$Y = 0.001X^{1.83}$,	$r = 0.98$

The input of suspended sediment from these major sources to the reservoir is estimated by using these equations. Suspended sediment is calculated as tons/day and summed for a month (Table 2).

Sediment from ungaged areas is estimated following the procedure used for estimating discharge from those areas. When total monthly sediment discharge in tons is plotted against total monthly water discharge in cfs for all gaged watersheds, the relation is:

$$Y = 0.154X^{1.223}, \quad r = 0.88$$

Knowing the previously established relation of discharge expressed as a percentage of Belmont discharge (Fig. 4), the sediment discharged from ungaged areas may be estimated. The ungaged areas are grouped (A, B, C) as in the hydrology analysis. The total discharge for the average size watershed of each group is computed. The total monthly sediment discharge, in turn, is calculated from the sediment load-discharge relation and is multiplied by the number of watersheds in the group giving a group total. The other groups are similarly analyzed, and the sum of the groups gives the total monthly sediment

Table 2. Suspended-Sediment Budget in Monroe Reservoir (tons)

Month	Belmont	Story	Maumee	Stephens Creek Gage	Ungaged	Total Input	Dam	Water Works	Total Output	Balance
Nov 75	197	250	251	19	248	965	32	19	51	914
Dec	1,143	561	2,306	72	437	4,519	332	17	349	4,170
Jan 76	1,190	594	1,604	58	443	3,889	711	18	729	3,160
Feb	1,414	610	1,064	48	373	3,509	503	17	520	2,989
Mar	339	130	1,187	50	43	1,749	607	17	624	1,125
Apr	45	14	35	9	65	168	106	17	123	45
May	29	9	11	2	43	94	33	15	48	46
Jun	23	7	19	6	30	85	32	16	48	37
Jul	3	4	10	9	9	35	33	18	51	-16
Aug	4	0	6	0	5	15	33	19	52	-37
Sep	4	0	5	0	4	13	33	19	52	-39
Oct	10	1	9	1	12	33	33	18	51	-18
Nov	13	2	10	1	15	41	33	16	49	- 8
Dec	6	1	9	1	7	24	33	16	49	-25
Total	4,420	2,182	6,526	276	1,734	15,139	2,554	242	2,796	12,343
Average	315	156	466	20	124	1,081	182	17	200	

contribution from the ungaged watersheds (Table 2). Total input is the sum of the gaged and ungaged watersheds.

Output of sediment is measured in the dam tailwater at the Harrodsburg gage (Fig. 1) and near the inlet to the Bloomington Water Works. The average sediment concentrations in those waters are 7.9 and 14.1 mg/l, respectively. These values times the total monthly discharges give total monthly sediment discharge.

During the 14-month period from November 1975 through December 1976, the total input to the reservoir was 15,139 tons, and total output was 2,796 tons. On an annual basis, these values are 12,970 and 2,400 tons, so 10,600 tons were contained in the reservoir. The trap efficiency is 81% which is slightly lower than the efficiency for reservoirs having a capacity-inflow ratio of 0.5 (Brune, 1953).

The average volume weight, dry weight/unit volume of bottom sediment determined in the laboratory from cores extracted from the lake bottom, is 47.4 lbs/ft^3. The annual rate of deposition of sediment is about 10 acre-feet. As the original storage capacity of the reservoir is 182,527 acre-feet, the annual storage loss resulting from sediment accumulation is about 1/100 of 1%. The annual accumulation in the reservoir is about 0.02 acre-feet or 25.5 tons/sq mi. For the 11-year lifetime of the lake, the calculated average thickness of bottom sediment is 0.13 in.

The input-output model does not take into account the variability of suspended sediment in the lake waters. The amount of suspended sediment varies with depth and location in the reservoir. Based upon correlated turbidity measurements, concentrations are generally

greater in the waters near the lake bottom than in the near-surface waters. This condition exists particularly during the summer months when the waters are thermally, as well as density, stratified. During the winter months when the waters are mixed, concentrations of suspended sediment are more uniform with depth.

Suspended-sediment concentration also varies downlake, and average load (mg/l) progressively decreases from basin DEF to basins C, B, and A (Fig. 1). When the average suspended load ($\underline{Y}$ in mg/l) of each basin is plotted against the cumulative percentage of each basin per lake area ($\underline{X}$), the relation is:

$$Y = 16.98 - 0.096X, \quad r = -0.99, \quad Se = 0.64 \text{ mg/l}$$

The rate of decrease varies seasonally and is more pronounced in the wetter, winter months than in the drier, summer months (Fig. 7).

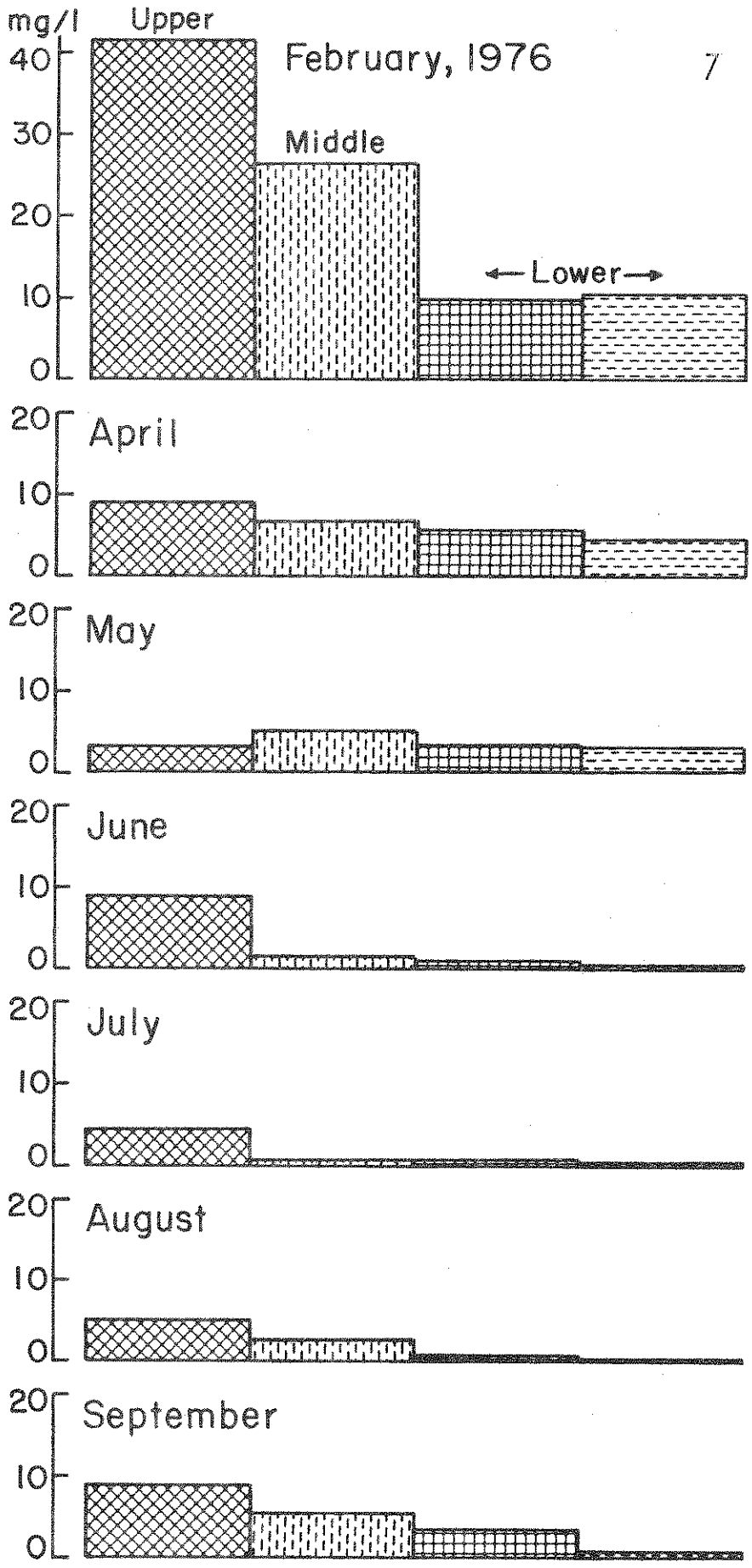
If deposition of load in the reservoir follows the transport relation, bottom sediment thickness should decrease from the upper to the middle and lower lake basins. This prediction will be re-examined in the discussion of bottom cores.

Survey-Fathometer Profiles

The second method for investigating sedimentation in the reservoir is by a systematic survey of the lake bottom using a Raytheon Recording Survey Fathometer Model DE 719 B. The accuracy of this instrument was checked on the reservoir in field conditions at 62 sites against manual lead and chain measurements. The water depths ranged from 4 to 44 ft. Fathometer depths relate to chain depths as:

$$Y = -0.1 + 0.97X$$
$$r = 0.99 \text{ and } Se = 0.45 \text{ ft}$$

Fig. 7. Average suspended-sediment concentrations in basins of Lake Monroe on monthly basis from wetter (February) to drier (September) periods. Downlake direction is from upper (segments E, F, and D, Fig. 1) to middle (C) and lower basins (B and A).


mg/l
Upper
February, 1976
7
40
30
20
10
0
Middle
Lower
20
10
0
April
20
10
0
May
20
10
0
June
20
10
0
July
20
10
0
August
20
10
0
September

The relation is almost 1:1 within a standard error of <0.5 ft. Bottom sediments must be >0.5 ft thick to be recognized on a fathometer profile.

The lake bottom was surveyed along 53 fathometer profiles across the lake which permits construction of a map of the bottom topography with a contour interval of 2 ft (open file, Water Resources Research Center, Indiana University). Maps previously available were the Allens Creek, Clear Creek, Elkinsville, and Unionville Quadrangles, 7.5 minute series, scale 1:24,000, contour interval 10 ft.

Fathometer profiles generally show "clean" bottoms (Fig. 8). Layering, suggestive of accumulated sediment of detectable thickness, is not evident. Yet, the instrument does detect aquatic weeds as in profile 20 toward the right bank.

Four survey-fathometer profiles of the current work are almost geographically coincident with sedimentation ranges of the Corps of Engineers that were surveyed during 1971 and 1973. A comparison can be made by relating depths of match points on fathometer profiles (Y) against those on the sedimentation ranges (X). Along profiles 6 and 17 in deeper water of the lower basin, the relations are:

$$(6) \quad Y = -0.759 + 1.00X$$
$$r = 0.99 \text{ and } Se = 0.79 \text{ ft}$$

$$(17) \quad Y = 0.43 + 1.02X$$
$$r = 0.99 \text{ and } Se = 1.4 \text{ ft}$$

Along 2 profiles and matching ranges in shallower water in the upper basin, the relations are:

(50) $Y = 1.367 + 0.886X$

$r = 0.99$ and $Se = 1.5$ ft

(53) $Y = 0.809 + 0.896X$

$r = 0.99$ and $Se = 0.4$ ft

With all match points combined, the relation is:

$Y = 0.708 + 0.988X$

$r = 0.99$ and $Se = 1.9$ ft

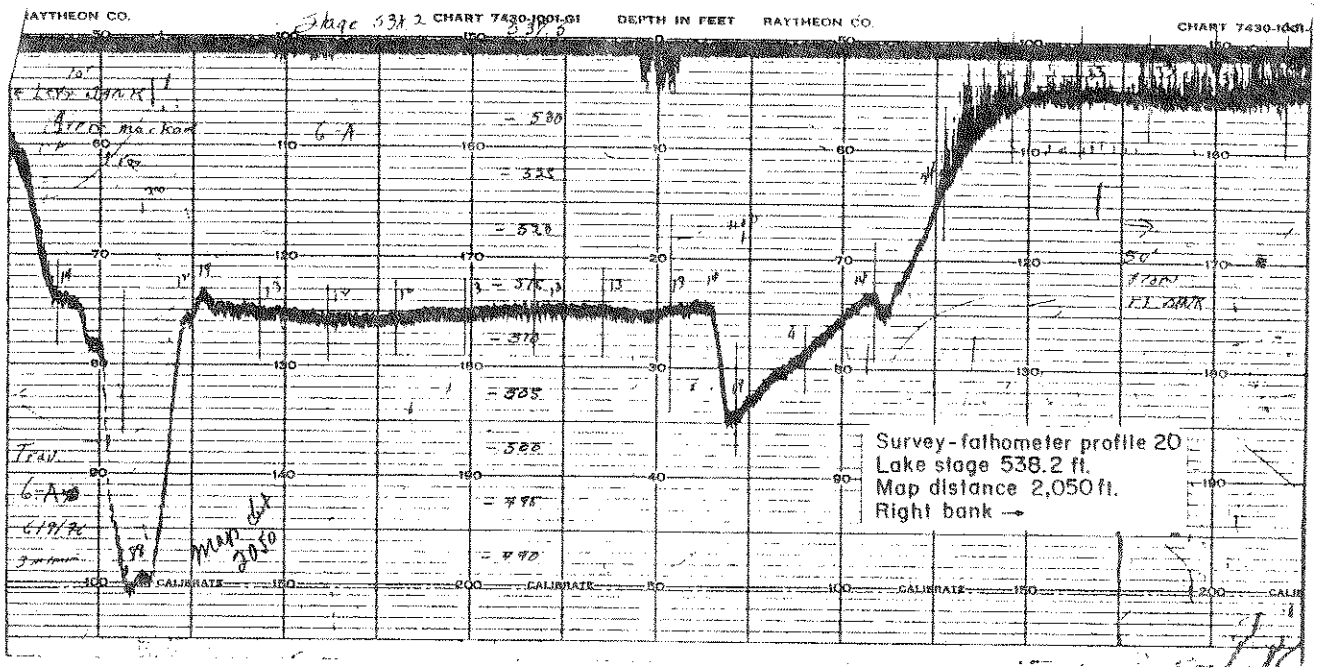
The deep water and combined comparisons are almost 1:1 indicating little change in bottom profile between the two surveys.

Bottom Coring

The third method for studying the sedimentation system of the reservoir involved coring the lake bottom to determine the actual amount of sediment. The coring device, fabricated for this work (Fig. 9A), consists of a Giddings 2-in O.D. soil-coring tube 4-ft long with bit. Rigid plastic tubes, 1 3/4-in O.D., fit snugly as liners. A trap valve consists of a standard rubber laboratory stopper with a central hole. A rubber flap is stapled on one side to the stopper to cover the hole. The stopper is inserted in the plastic liner, and this assembly is inserted, stopper first, in the coring tube. The liner assembly is secured by screwing the bit to the coring tube.

A drive-hammer assembly consists of a collar with attached steel rod. A 40-lb weighted platform rides up and down on the rod. The collar is secured to the coring tube with a pass-through bolt. One cable is attached to the steel rod, and a second cable is attached to the weighted hammer.

Fig. 8. Survey-fathometer profiles of bottom of Lake Monroe. Locations of profiles given on Plate 2. Note "clean" bottoms or lack of "double" reflection surfaces that would indicate accumulation of sediment. Ragged reflection pattern along right bank in profile 20 shows aquatic plants.


RAYTHEON CO.
CHART 7430-1001-01
DEPTH IN FEET
RAYTHEON CO.
CHART 7430-1001-01
Survey-fathometer profile 20
Lake stage 538.2 ft.
Map distance 2,050 ft.
Right bank →

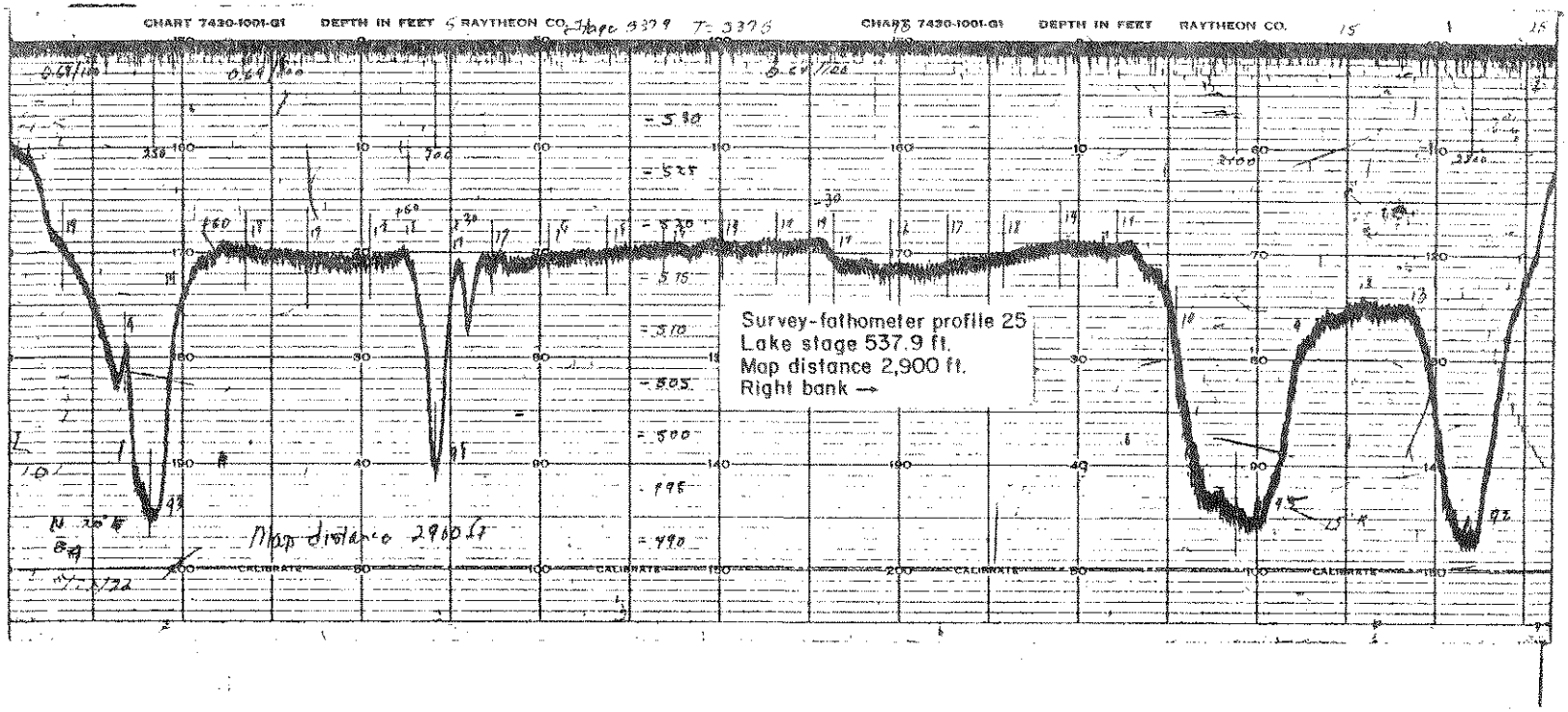
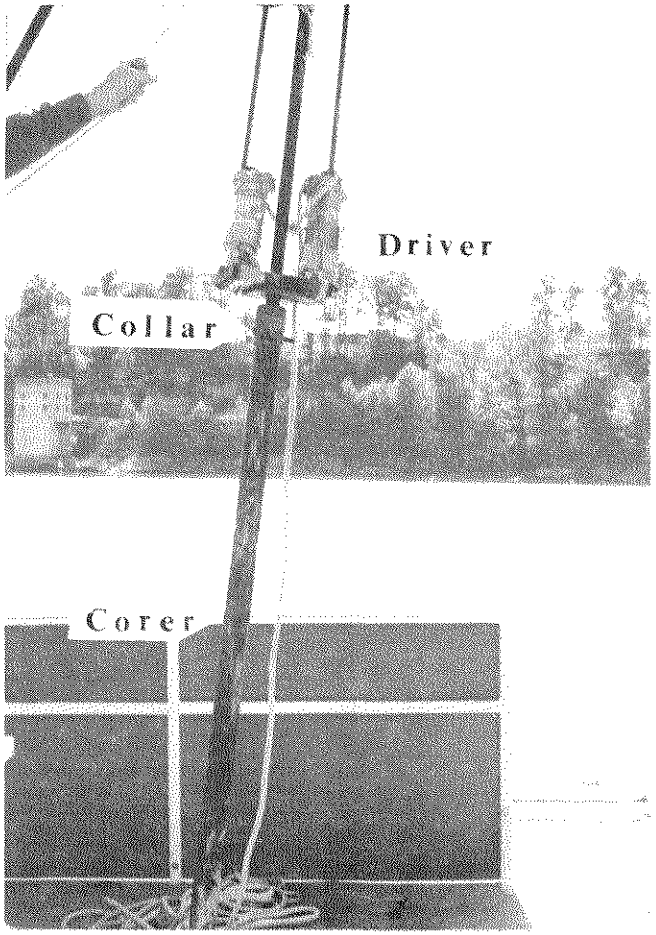
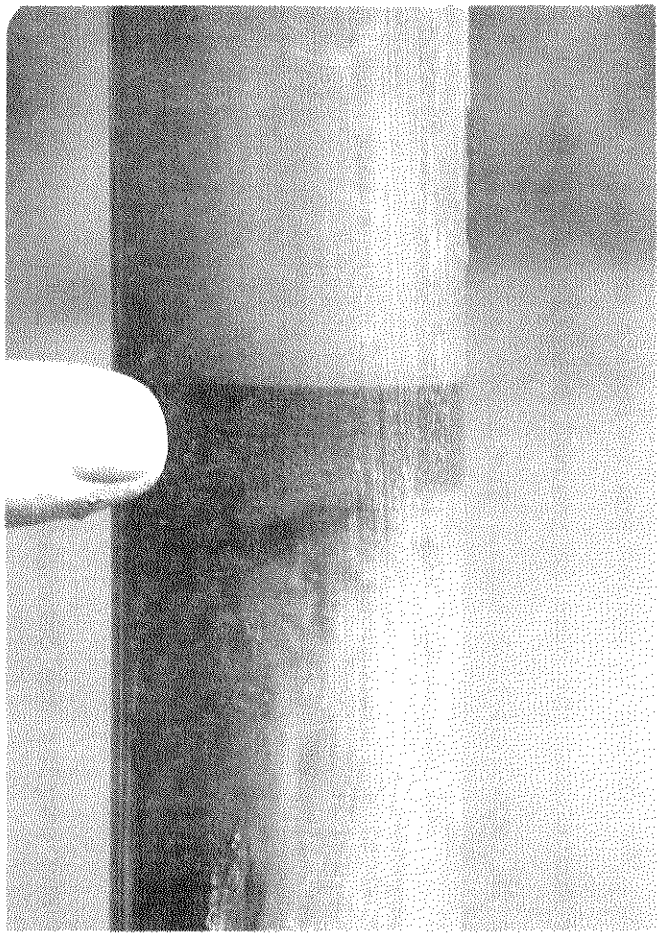


CHART 7430-1001-01
DEPTH IN FEET
RAYTHEON CO.
CHART 7430-1001-01
DEPTH IN FEET
RAYTHEON CO.
Survey-fathometer profile 25
Lake stage 537.9 ft.
Map distance 2,900 ft.
Right bank →

Fig. 9. (A) "Home-made" coring device for bottom sampling. (B) Core in plastic liner extracted from lake bottom. Finger indicates accumulated sediment shown as dark band in core that overlies pre-existing soil now submerged by lake.


Driver
Collar
Corer



The device is lowered to the bottom by use of the cables from the securely anchored work boat. Upon contact with the bottom, the weighted hammer is raised by the second cable and then allowed to free-fall against the collar driving the coring tube into the lake bottom. Hammering continues until the coring tube penetrates to a desired depth. The device is pulled and raised to the boat. The plastic liner containing the core is removed from the coring tube, and the liner is capped at both ends. The liner and core are taken to the laboratory and placed in an upright freezer at -20°C. Freezing limits chemical and biological alteration and hardens soft sediment and gel-like ooze. Later the cores are removed from the liners by applying hot water to the exterior of the liner to break the frozen core, and the core is extruded from the liner. The frozen core is sawed into increments for laboratory processing. Excellent cores and samples are obtained by this technique (Fig. 9B).

In the shallow-water upper basin above the causeway, 31 cores were extracted along 4 profiles across the inlet from North Fork of Salt Creek (Fig. 1). Five cores were extracted across the lake at the mouth of the inlet from Middle and South Forks. One additional site was in the basin above the causeway, and another was in the Middle inlet. Other cores were extracted from the lake bottom under progressively deeper water downlake toward the dam. This last phase of coring is incomplete, and more work needs to be done in the middle and lower basins.

To properly identify lake sediment and separate it stratigraphically, properties of soils that existed on the alluvial flats of Salt Creek Valley must be known. Those soils are now submerged

by the lake water. According to prior soil survey (Bushnell and Fowler, 1928; Tharp and others, 1928), the Huntington fine sandy loam was confined to the channel pattern of Salt Creek, and the Calhoun silt loam, Waverly silty clay loam, Waverly silt loam, and Holly silt loam were on the floodplain with the last two soils being dominant. Consequently, these two soils were studied and sampled in the field on the Salt Creek floodplain below the dam and above the lake. Soil cores from 3 sites were collected and returned to the laboratory for study (Fig. 10). Coring sites in the deeper water of the reservoir were restricted to areas where the two dominant soil types were mapped during pre-lake soil survey. The sediment is readily distinguishable from the pre-existing soil (Fig. 9B) and morphologically differs in color, either lighter or darker value, and less firm than the soil. The sediment may be like an ooze or even a gel and has greater amount of $<2\mu$ clay. Average dry bulk densities of the sediment and immediately subjacent soil are 0.76 and 1.22 g/cm^3, respectively.

The pre-existing Holly and Waverly soils of the reservoir have been altered during their 11-year period of submergence, and to determine the kinds of alterations, physical and chemical properties were analyzed of the 3 soil profiles outside the reservoir and 6 bottom cores from the lower middle and upper basins of the reservoir (Tables 3, 4, 5). The floodplain soils have dark grayish-brown (2.5Y hue) surface horizons and olive, olive-brown, and yellowish-brown subsoil horizons (5Y, 2.5Y, and 10YR hues). In contrast, the cores of submerged soils generally are greenish-yellow to olive-gray and even bluish-green (5GY, 5BG, and 5Y hues).

Table 3. Selected Properties of Soils, Salt Creek Floodplain

Depth	Clay	Organic Carbon	Fe		Mn	P	
			Total	Fe^{2+}		Total	Organic
(in)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)
Soil Site No. 1							
0-1	23.4	1.2	0.89	0.00	0.02	547	191
1-2	26.3	1.4	0.88	0.00	0.02	552	110
2-4	26.3	0.7	0.94	0.00	0.02	523	9
4-6	24.8	1.4	0.97	0.00	0.02	412	21
6-8	20.4	1.0	0.92	0.00	0.02	494	46
8-10		0.9	0.87	0.00	0.02	468	108
10-15	19.6	0.8	0.86	0.00	0.02		134
15-20	18.9						
20-25	21.1		0.52		0.01		
25-30	23.3		0.17				
30-40	26.7		1.21				
Soil Site No. 2							
0-1	19.1					393	144
1-2	22.7					411	134
2-4	23.8					398	167
4-6	22.2					532	107
6-8	26.8					395	113
8-10	27.7					351	79
17-24	26.4						
24-29	25.5						
29-36	24.6						
36-42	24.2						
42-48	24.2						
Soil Site No. 3							
0-1	15.7	1.2		0.02		449	221
1-2	11.3	1.2	0.76	0.01	0.05	531	
2-4	8.3	1.1	0.83	0.00	0.04	403	192
4-6	13.1	1.4	0.78	0.00	0.03	398	77
6-8	14.4		0.68	0.01	0.03	304	89
8-10	14.7	0.6			0.04	407	168
13-18		0.7	1.10				
18-23	11.0						
23-31	17.7						
31-37	8.5						
37-44	17.9						

Table 4. Selected Properties of Bottom Cores, Lake Monroe

Depth	Clay	Organic Carbon	Fe		Mn	P	
			Total	Fe^{2+}		Total	Organic
(in)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)
Core 1A1							
0-1	Gel	1.6	2.08		0.09	356	
1-2	23.6	1.0	1.01	0.89	0.04	290	
2-3	18.9	0.7		0.47		207	53
3-4	18.1	0.5	0.78		0.03	190	68
4-5	21.6	0.4		0.37		108	
5-7	20.8	0.3	0.74		0.03	133	71
7-9	15.1	0.3	0.76	0.32	0.02	238	36
9-10	20.1	0.2	0.68	0.29	0.03	150	50
10-12			0.56		0.02		184
Core 6A1							
0-1	25.1	1.1	1.55	0.59	0.10		133
1-2	15.8	0.4	0.80	0.47	0.05		73
2-3	13.6	0.5	0.81	0.50	0.04	403	21
3-5	14.0	0.5				376	84
5-7	11.3	0.4	0.67	0.28	0.03	321	22
7-9	9.5	0.2	0.88	0.16	0.04	98	
9-11	9.1	0.2	0.85	0.02	0.04	380	72
11-15	8.9	0.2	0.89	0.01	0.03		146
15-18	10.0	0.2					
Core 9.3A1							
0-1	13.1	0.9		0.34		656	
1-2	11.7	0.8	0.56	0.22	0.03	322	26
2-3	12.2	0.4	0.69	0.15	0.02	260	11
3-4	10.7	0.2	0.88	0.11	0.04	247	11
4-5	10.4	0.1	0.76	0.02	0.03	213	2
5-6	10.8	0.2	0.74	0.01	0.03	251	8
6-9	11.3	0.1	0.84	<.01	0.03	281	6
9-12	10.1		0.99	<.01	0.03	235	
12-15	12.2	0.1	0.75	<.01	0.03		
15-18	13.1	0.1	0.72	<.01	0.03		
22-25	9.8	0.1	0.67	<.01	0.02		

Table 5. Selected Properties of Bottom Cores, Lake Monroe

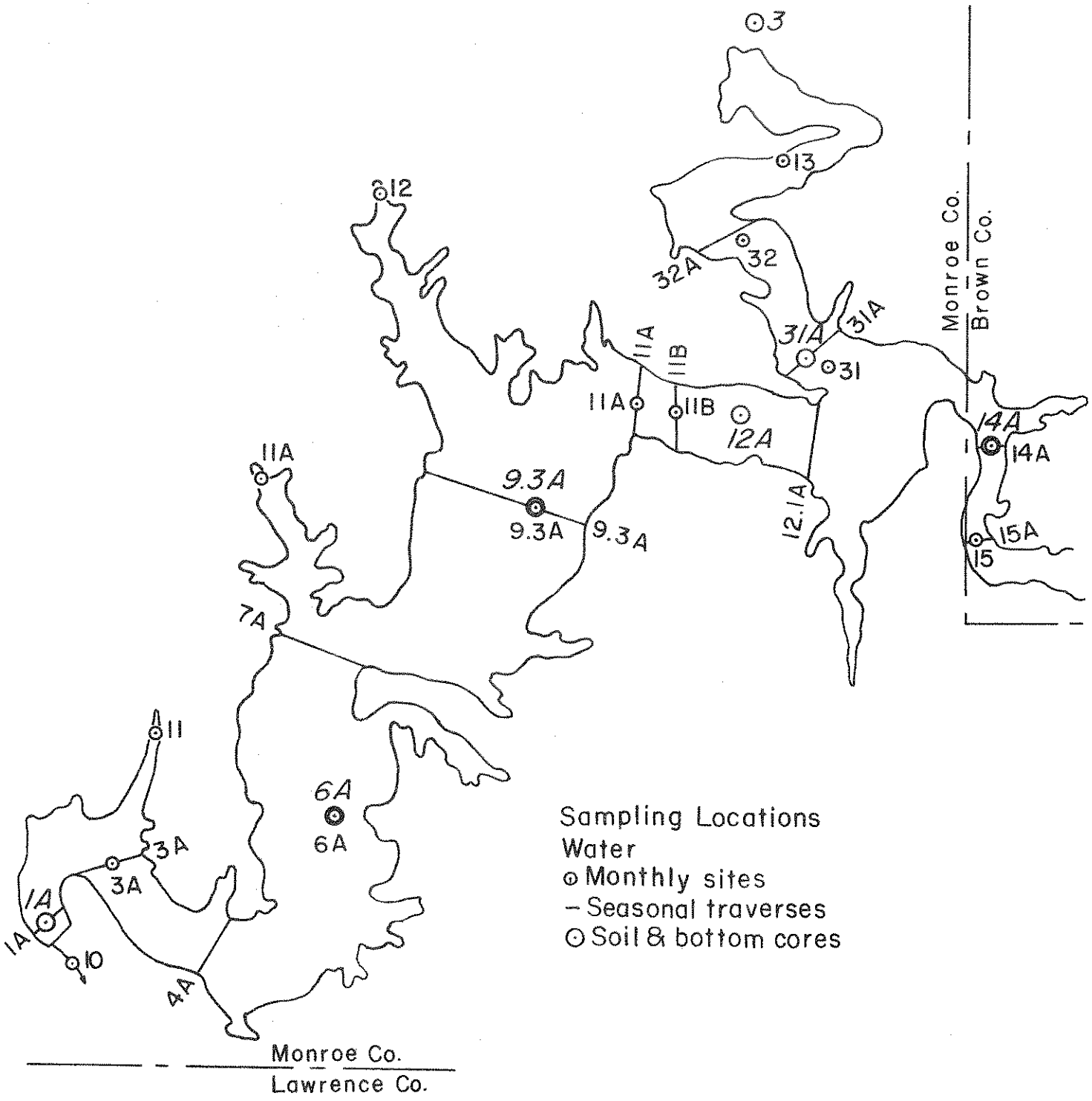
Depth	Clay	Organic Carbon	Fe		Mn	P	
			Total	Fe^{2+}		Total	Organic
(in)	(%)	(%)	(%)	(%)	(%)	(ppm)	(ppm)
Core 12A1							
0-1	39.4	1.4	1.16	0.42	0.05	516	
1-2	18.0	1.2	0.68	0.23	0.03	222	8
2-3		0.8	0.58	0.33	0.03	188	7
3-4	15.2	1.0	0.51	0.53	0.01	344	7
4-6		0.8	0.50	0.40	0.02	217	33
6-7	17.1	0.8	0.52	0.35	0.02	337	43
7-9	15.7	0.7	0.49	0.36	0.02	286	43
9-11	12.2	0.5	0.53	0.44	0.02	267	
11-14			0.48	0.28	0.02	229	43
14-16			0.46	0.30	0.02		65
16-18			0.44	0.16	0.03		117
Core 31A1							
0-1	37.2	1.4	1.04	0.39	0.04	702	106
1-2	21.2	1.0	0.80	0.33	0.03	481	177
2-3	26.4	1.0	0.82	0.27	0.03	367	63
3-5	21.1	0.8	0.84	0.28	0.03	511	36
5-7	25.3	0.8	0.79	0.28	0.03	465	63
7-9	24.1	0.8	0.62	0.25	0.02	379	16
9-13	32.5	0.8					
14-18		0.9					
Core 14A1							
0-1	46.4	0.7	1.27		0.05	240	
1-2	12.7	0.5	1.26	0.98	0.04	267	67
2-3	13.2	0.4	0.99		0.02	59	6
3-4	18.1	0.4	0.77	0.51	0.02	116	
4-5	15.8	0.3	1.04	0.52	0.06	160	
5-7	13.8	0.2	0.97	0.52	0.06	330	
7-9	15.6	0.1	0.70	0.36	0.04	279	
9-13	12.2	0.2	0.73	0.35	0.05	129	
13-16			0.73	0.12	0.05		59

These latter colors indicate gleying or reducing conditions. Note the differences in total and reduced (Fe^{2+}) iron in the profiles and cores. All of the samples contain dithionite extractable iron, but there is little or no reduced iron in the floodplain soils (Table 3). In the submerged cores, Fe^{2+} is highest just beneath the lake bottom and progressively decreases to a depth of a foot or more (Tables 4, 5). Calculated as a percentage of total Fe, Fe^{2+} ranges from 30 to 90%.

The reducing environment extends a foot or more into the former floodplain soils and relates to the chemistry of the layer of water just above bottom in the reservoir (Table 6). The pH values range from 6.9 to 8.5 as water depth progressively decreases from 34 to 6 ft from site 1A to sites 14A and 31A. The pH of interstitial water in the bottom sediments and submerged soils is 6.5 to 6.6 as measured on field-moist samples of cores 1A, 12A, and 31A. The weighted, average pH of air-dried samples of bottom sediments and submerged soils range from 4.2 to 4.9 to depths as much as 25 in below the lake bottom. These values are similar to weighted averages of the non-submerged floodplain soils whose weighted, average pH values are 4.6 to 5.7 to depths of 36 in in the profiles.

Dissolved oxygen in the bottom layer of lake water ranges from 3.2 to 9.4 mg/l and is minimal during the summer. Redox potential varies from 180 to 424 mv as depth decreases from 34 to 10 ft but then decreases in shallower water. Within the ranges of Eh and pH, the solid and dissolved forms of Fe are expectably in the reduced state (Hem, 1970).

Fig. 10. Soil-sampling sites below the dam (1, 2) and above the lake (3). Bottom-core sites within the reservoir (1A ... 31A). Water-sampling sites of the reservoir (3A ... 32) on monthly basis, and water-sampling traverses (1A ... 32A) on a seasonal basis.


3
13
12
32A
32
31A
31A
31
Monroe Co.
Brown Co.
11A
11B
11A
11B
12A
14A
14A
11A
9.3A
9.3A
9.3A
12.1A
15A
15
7A
11
6A
6A
3A
3A
1A
1A
10
4A
Monroe Co.
Lawrence Co.
Sampling Locations
Water
⊙ Monthly sites
– Seasonal traverses
⊙ Soil & bottom cores

⊙2

10

⊙1

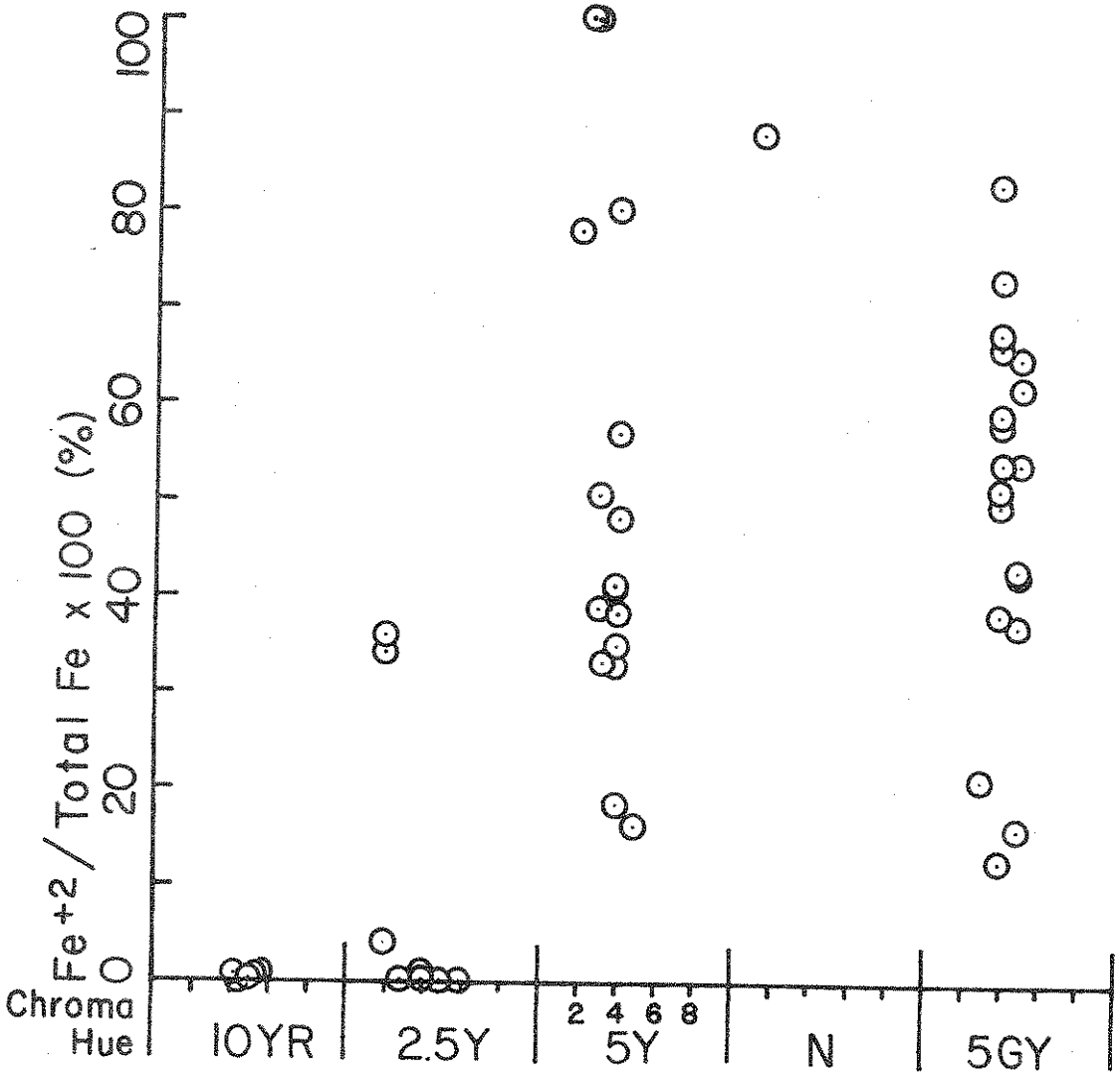
Table 6. Properties of Bottom Layer of Water at Sites in Monroe Reservoir

Site	Date	Temp (C)	pH	DO (mg/l)	ORP (mv)	Water depth (ft)
1A	5/12/76	15.0	6.6	5.6	310	34
	6/14/76	16.7	6.5	1.0	310	
	6/17/76	17.7	6.6	0.6	340	
	8/4/76	16.8	6.9	0.05	-350	
	8/24/76	21.5	6.7	0.08	70	
	9/21/76	22.5	7.1	7.3	370	
	10/19/76	15.7	7.0	7.8	210	
		18.3 ± 2.8	6.9 ± 0.3	3.2 ± 3.5	180 ± 255	
6A	5/12/76	15.8	6.9	7.9	280	25
	6/17/76	20.0	6.7	3.2	370	
	8/4/76	20.5	6.9	0.6	550	
	8/24/76	26.4	8.3	9.1	270	
	9/21/76	22.0	7.2	7.2	340	
		20.9 ± 3.8	7.2 ± 0.6	5.6 ± 3.6	362 ± 113	
9.3A	5/5/76	15.8	7.3	9.3	550	21
	6/17/76	23.5	7.2		310	
	8/4/76	25.3	7.0	6.6	270	
	8/24/76	24.5	6.7	3.7	400	
	9/21/76	22.0	7.3	7.6	330	
		222 ± 3.7	7.1 ± 0.3	6.8 ± 2.4	372 ± 110	
12A	5/5/76	15.8	7.4	9.5	490	10
	6/17/76	25.0	7.4	6.7	250	
	8/5/76	25.8	8.4	2.4	830	
	8/24/76	25.3	7.2	6.8	290	
	9/21/76	21.5	6.9	7.6	260	
		22.7 ± 4.2	7.5 ± 0.6	6.6 ± 2.6	424 ± 247	
14A	6/17/76	27.6	8.6	7.2	220	6
	8/5/76	25.2	8.6	7.2	220	
	8/24/76	26.5	8.8	8.7	220	
	9/21/76	22.8	7.6	8.1	340	
	10/19/76	11.9	7.2	9.8	170	
		22.8 ± 6.4	8.2 ± 0.7	8.2 ± 1.1	234 ± 63	
31A	5/5/76	15.5	8.2	10.4	220	6
	6/17/76	28.3	8.7	7.9	210	
	8/5/76	25.0	8.8	7.7	113	
	8/24/76	27.0	9.4	10.5	116	
	9/21/76	21.6	8.2	8.7	260	
	10/19/76	11.5	7.5	11.0	120	
		21.5 ± 6.7	8.5 ± 0.7	9.4 ± 1.4	173 ± 65	

Reduction of iron in the bottom sediments and pre-existing soils now submerged is further shown by a comparison of Fe^{2+} and the soil colors. As percent Fe^{2+} to total Fe increases, colors shift from 10YR (Munsell soil color) to 2.5Y and then to 5Y, N, and 5GY (Fig. 11). This relation of reduction of Fe and color conforms to prior work in soils (Daniels and others, 1960).

Physical and chemical properties of the bottom cores from the lake also permit separation of lake sediment from the pre-existing soils (Tables 3 - 5). Clay ($<2\mu$) abruptly decreases from sediment to soil (Cores 6A, 12A, 14A, 31A). Organic-carbon content may decrease abruptly (Cores 1A, 6A, 12A, 31A). Phosphate, total or organic, decreases abruptly (Cores 1A, 6A, 9.3A, 12A, 31A) as does iron (Cores 1A, 6A, 12A, 31A). All of these data show that little sediment, only an inch or so, has accumulated in the middle and lower basins of the reservoir during its 11-year life. The averages of thickness of sediment along the previously mentioned traverses in the upper basin are 2.1, 2.2, 2.3, and 4.0 in. These thicknesses are also quite minor for the 11-year history of the reservoir. The thickness data verify the prediction from the suspended-sediment model down reservoir (Fig. 7).

Fig. 11. Relation of percent of ferrous iron (Fe^{2+}) in total iron fraction to Munsell soil color hue and chroma in bottom cores from Lake Monroe.


Fe+2 / Total Fe x 100 (%)
0
20
40
60
80
100
Chroma
Hue
10YR
2.5Y
2 4 6 8
5Y
N
5GY

11

WATER CHEMISTRY

The locations of water-sampling sites are designed to monitor (1) possible differing water chemistry from source areas, (2) the water chemistry of the basins of the reservoir, and (3) the dimensional distributions of water chemistry in the lake. Consequently, at specific sites (Fig. 10) depth profiles are measured in the field, and samples were collected for analysis on a monthly basis. Other sites sampled in this program are the Stephens Creek, Belmont, Nashville, Story, and Maumee gages, the confluence of Middle and South Forks of Salt Creek, and two sites in the inlet of Crooked Creek (Fig. 12). Field measurements also are made to depth along selected traverses and samples were collected and analyzed in the laboratory on a seasonal basis.

Field measurements are made with a Hydrolab Multisensor Probe and consist of temperature, pH, conductivity, dissolved oxygen, and redox potential. Laboratory analyses include alkalinity, hardness, Cl, PO_4 (total orthophosphate), SO_4, SiO_2, and NO_3. Standard methods are used (APHA, 1975), but NO_3 is determined by specific-ion electrode. Cations (Ca, Mg, K, Na, and Fe) are analyzed by atomic-absorption spectrometry, and turbidity is measured in a Hach Turbidimeter, Model 2100A.

Source Waters

Differences in water chemistry may be anticipated relative to bedrock, surficial sediment, and soil distributions previously described in the reservoir watershed (Fig. 2). The difference in

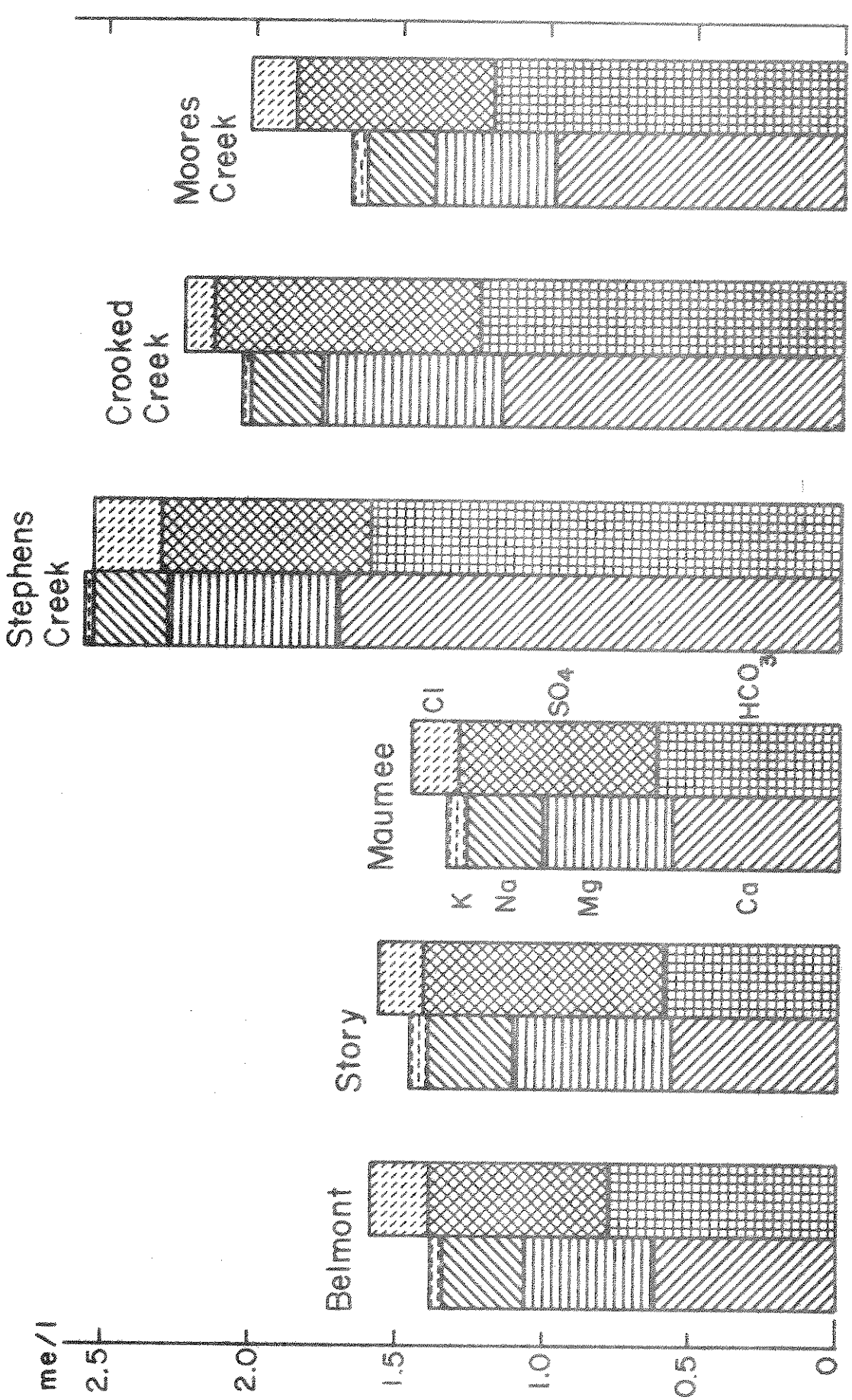


Fig. 12. Average chemistry of source-area waters of Lake Monroe compared by EMP balance. 12

chemistry of waters from the different terrains is demonstrated by the average EPM balance at sites (Fig. 12). In Stephens Creek and Moores Creek, concentrations of Ca^{+2}, Mg^{+2}, and HCO_3^{-1} are appreciably greater than those in North Fork (Belmont), Middle Fork (Story) and South Fork (Maumee). The former pair drains limestone terrain, and the latter group drains siltstone terrain. There is little difference in concentrations of Na^{+1}, K^{+1}, SO_4^{-2}, and Cl^{-1}. Crooked Creek is an anomaly. Its water chemistry is like that from carbonate terrain, but its watershed is emplaced on siltstone, and carbonate rocks are not known to occur there. The differing waters mix in the reservoir.

The chemistry of waters from source areas also vary with discharge. For example, at the Belmont gage alkalinity (A) and hardness (H) in mg/l relates to discharge (Q) in cfs as:

$$A = 66.381 - 16.1594 \log Q$$
$$r = -0.80 \text{ and } Se = 11.5 \text{ mg/l}$$
$$H = 77.212 - 10.7624 \log Q$$
$$r = -0.75 \text{ and } Se = 8.6 \text{ mg/l}$$

Phosphate (P) in µg/l relates to discharge (Q) as:

$$P = 24.382 + 0.1338 Q$$
$$r = 0.97 \text{ and } Se = 20.1 \text{ µg/l}$$

The ranges in alkalinity, hardness, and phosphate are 20 to 89 mg/l, 29 to 83 mg/l, and 7 to 368 µg/l as discharge varies from <1 to 2,470 cfs. As input to the lake, concentrations of alkalinity and hardness (as $CaCO_3$) decrease as supply of water from contributing watersheds increases. Ions such as Ca^{+2}, Mg^{+2}, Na^{+}, and K^{+} have similar relations with discharge at the gages.

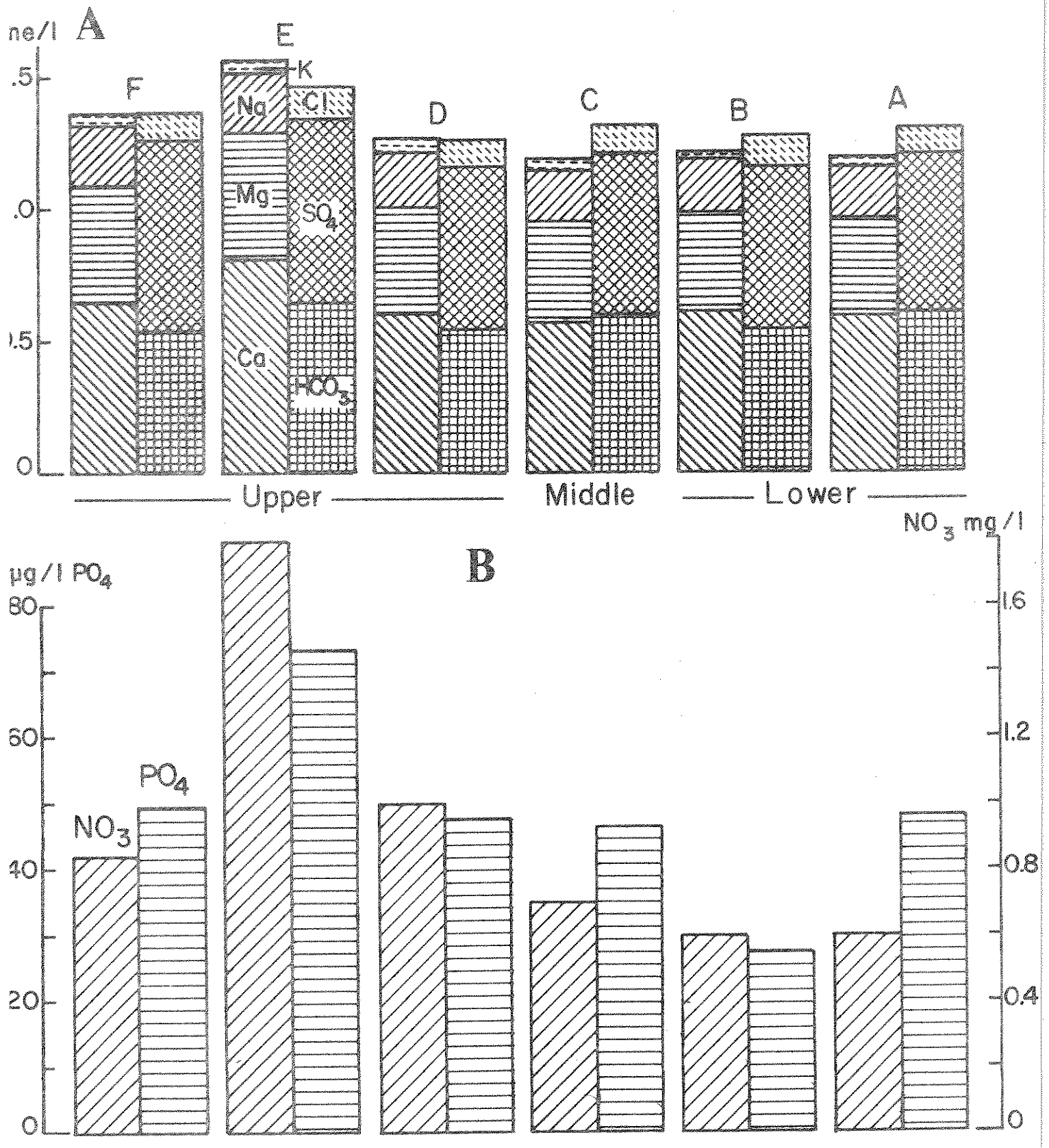
Conversely, phosphate concentrations increase with discharge at the Belmont and Maumee gages, but there is no statistical relation between phosphate and discharge at the Story gage. Where there is a concentration-discharge relation, the regression is interrupted at a discharge range of 200 to 300 cfs. Below this range phosphate increases as discharge increases. Within the range, phosphate decreases as discharge increases, but above the range the direct relation again exists. The interruption of direct relation may be due to an association between phosphate and suspended solids in contrast to phosphate in solution. At higher discharges most of the phosphate may be associated with particulate matter (Porter, 1975). At the Belmont and Maumee gages phosphate concentration (Y) relates to concentration of suspended solids (X) as:

$$Y = 35.103 + 0.661X + 0.0021X^2, \; R^2 = 0.94$$

Some chemical constituents show no relationship to source-area discharge, such as chloride and iron, or show erratic relations, such as sulfate and nitrate. Sulfate may increase with increase in discharge but then decrease with further increase in discharge. Nitrate concentrations vary seasonally, and this trend overrides any distinct relationship to discharge.

Lake Waters

Waters from the source-area watersheds mix readily in the basins of the reservoir. Based on the EPM balance of dominant cations and anions, there are no statistically significant differences between the chemistry of the waters of the individual basins (Fig. 13). The dominant ion concentrations are approximately the same from the upper



Fi . 13. (A) Average composition of waters of basins of Lake Monroe. See Fig. 1 for lake segments A ... F. (B) Average concentrations of nitrate and phosphate in basins of Lake Monroe.

basin above the causeway downlake to the middle basin and to the two parts of the lower basin (cf. Fig. 1). However, ion concentrations are significantly greater in the waters of the inlets from North Fork Salt Creek and Middle and South Forks. These waters join and mix in the upper basin and attain the general composition of the lake water. Input from source areas downlake has little effect on the chemistry of lake water even in area of carbonate rocks. The composition of inflow from North, Middle, and South Forks Salt Creek basically establishes the nature of the lake water.

Concentrations of nitrate (mg/l) and phosphate (µg/l) not only vary among the basins of the lake, but they also vary seasonally lake-wide. During a season (November 1975 - February 1976), the average concentrations of the constituents was greatest in the inlet of North Fork Salt Creek and decreased in the upper basin above the causeway (Fig. 13). The composition in the inlet of Middle and South Forks differed little from that of the upper basin. From the upper basin nitrate concentrations decreased downlake, but phosphate concentrations varied little except for a discrepantly lower value in the upper part of the lower basin. Seasonal variations lake-wide show greater concentrations in colder months (Fig. 14).

Vertical profiles show that the lake waters on an annual basis are stratified about 33% and nonstratified about 67% of the time. One profile in the middle basin near site 9.3A (Fig. 10) shows the change from stratification during September 1975 through turnover in October and nonstratification through late fall and into winter to February 1976 (Fig. 15). In September the thermocline at a depth of 27 ft separated the warmer (>17°C) epilimnion from the cooler

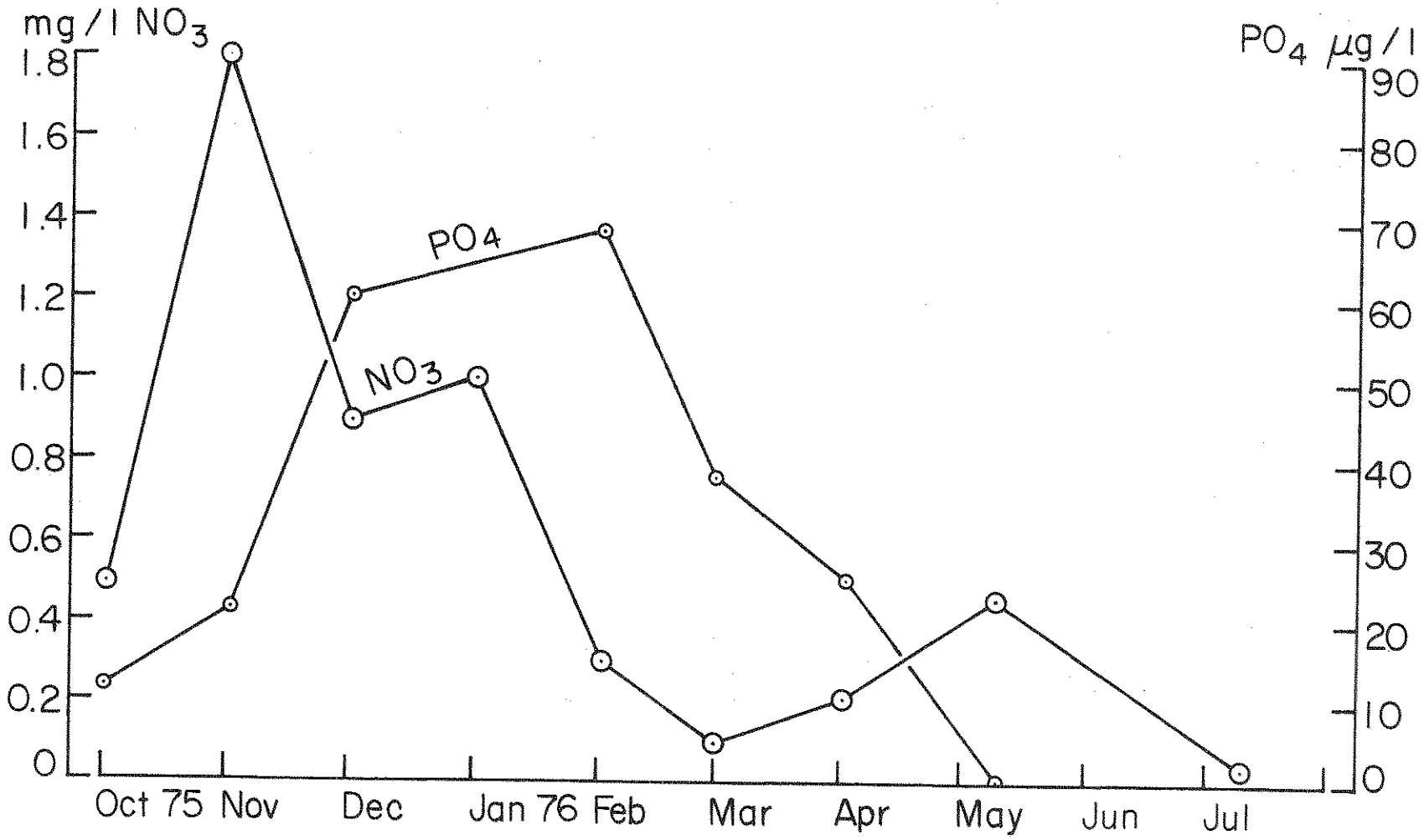


Fig. 1. Seasonal changes in average concentrations of nitrate and phosphate for Lake Sonoma as a whole.

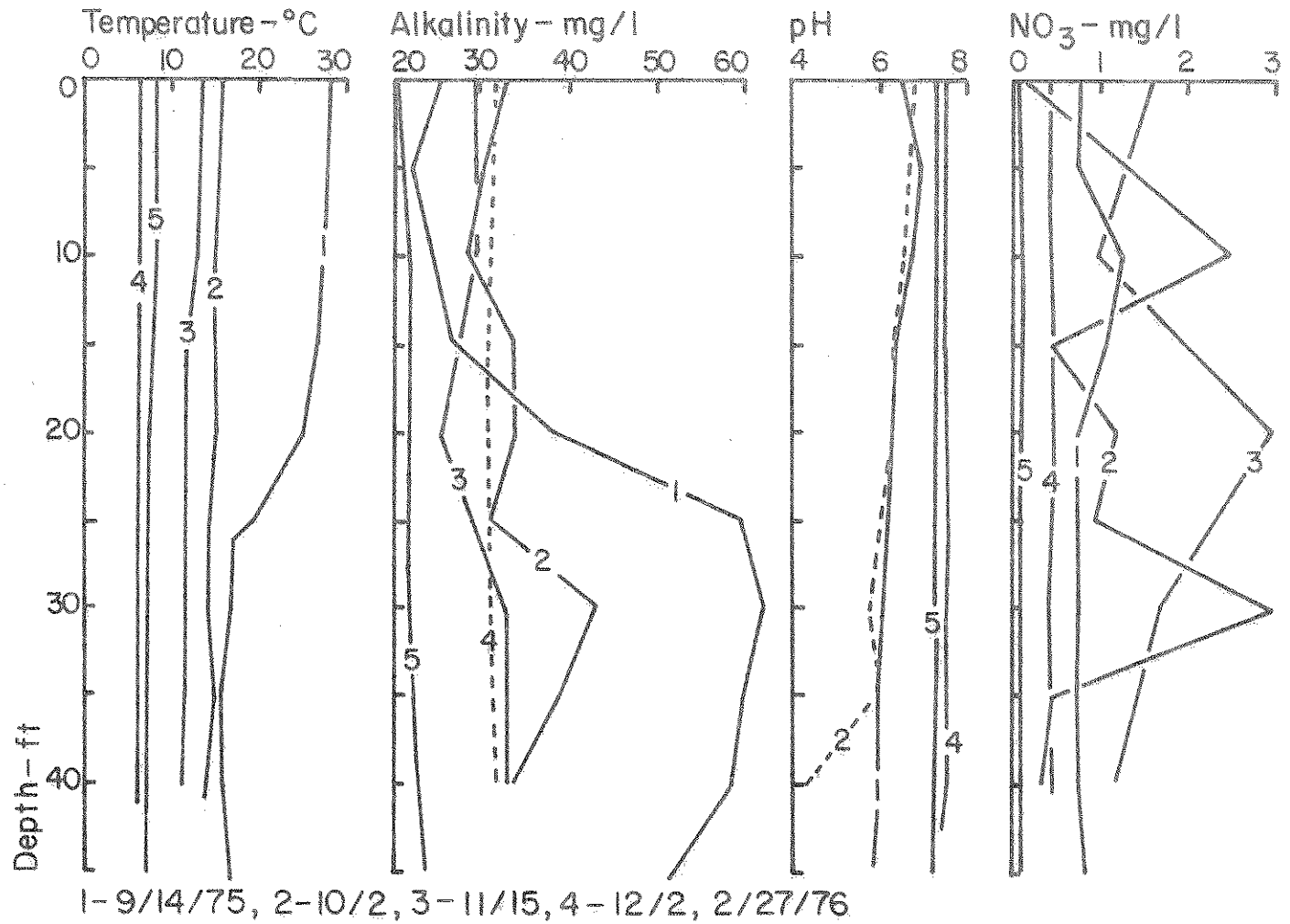


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Fig. 1-. "Turnover" of Lake Monroe water illustrated sequentially from summer to winter at a site in middle basin.

(<17°C) hypolimnion. By October 2, turnover had occurred and the temperature profile was essentially uniform to depth (≈15°C). In the following months the water cooled to 7° - 8°C but maintained a uniform vertical profile.

Note the corresponding change for concentration of alkalinity from a condition of stratification to nonstratification (Fig. 15). The pH profiles change from a pseudo-stratification of ≈7.0 in the upper water to ≈6.0 or less in the lower water to a uniform vertical distribution of 7.2 to 7.4. The nitrate profile accordingly changed from an erratic stratification of greater concentrations to a uniform vertical distribution of lower concentration.

Reversed cyclic changes at a site may be traced from a winter to a following summer. The site is along sampling traverse 11B in the upper basin above the causeway (Fig. 10). Temperature profiles are uniform to depth but mean temperature progressively increases from January into April 1976 (Fig. 16). During May the epilimnion began to develop as the upper waters warmed, and in the following summer the stratification is well defined. The pH profiles are uniform and increase in average values and then decrease as they become weakly stratified. Profiles of dissolved oxygen and conductivity show systematic and progressive changes to well-defined stratified systems. Dissolved oxygen decreases and conductivity increases. The extremely low values of dissolved oxygen in the hypolimnion causes the summertime reducing environment that results in gleying of the bottom sediments and submerged soils. See Sedimentation System: Bottom Coring.

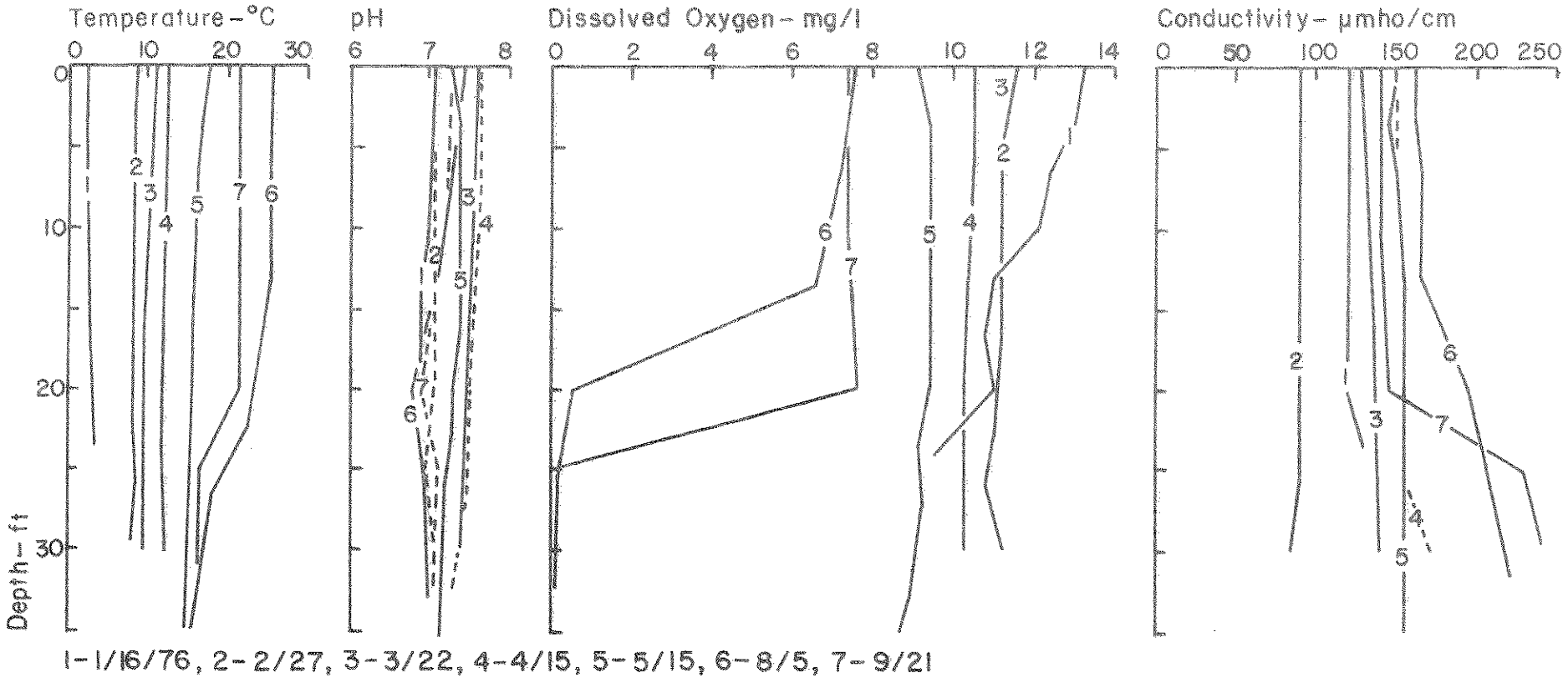

Fig. 16. Stratification of Lake Monroe water illustrated sequentially from winter to summer at a site in upper basin.

The stratification cycle timewise fits the inflow-outflow (replacement) system of the reservoir. The waters are stratified during May - October and coincide with periods of low inflow-outflow (Pl. 1). During the time when the lake waters are non-stratified, November - April, or mixed, the inflow-outflow systems operate with much greater volume of water. Consequently, the chemical system of the reservoir may be flushed during the replacement cycle of 4.3 mos as calculated for the period December 1975 - April 1976. See Hydrologic Circulation: Inflow-Outflow System Test.

Based upon the EPM balance of ions, the water chemistry of the lake relates to the inflow-outflow-storage model. As previously noted, the concentrations of Ca^{+2}, Mg^{+2}, and HCO_3^{-1} are inversely related to discharge from source-area watersheds, and the concentration of SO_4^{-2} increases and then decreases with increasing discharge. Also noted previously (Fig. 13A) is the ready mixing of lake waters regardless of basin. During periods of greater inflow during the wet season and corresponding higher stages of the lake (Pl. 1: November 1975 into March 1976), concentrations of Ca^{+2}, Mg^{+2}, HCO_3^{-1}, and SO_4^{-2} are relatively low in the lake water. In the EPM balance (Fig. 17: February 27, stage 540.5 ft) the sum of the cations is <1.0 me/l and the sum of the anions is slightly >1.0 me/l. The low ion concentrations result from dilution as the capacity of the reservoir increases.

During periods of lesser inflow during the dry season and corresponding lower stages of the lake (Pl. 1: May into November 1976) the ion concentrations become relatively higher in the lake

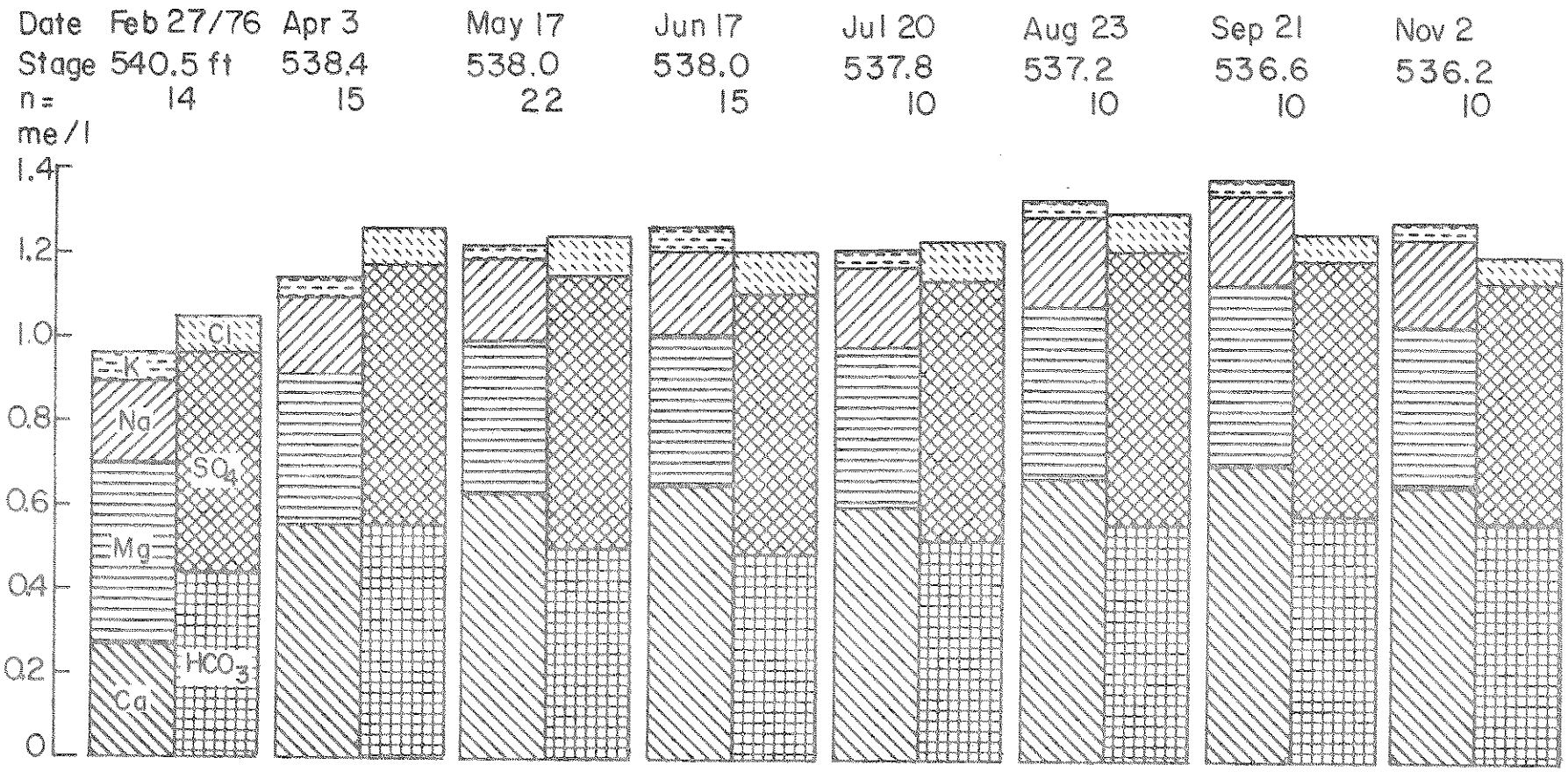

Fig. 17. Average compositions of waters of middle and lower basins of Lake Monroe to depth of 10 ft. Composition relates to lake stage. Lesser ion concentrations are during higher inflow-higher stage period (February). Greater ion concentrations are during lower inflow-lower stage periods (May - November). Greater inflow causes dilution.

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water. In the EPM balance (Fig. 17: May 17 to November 2), the sums of the cations and the anions are ≈1.2 me/l or greater. During this period, the lake stage was at or lower than the low-flow regulation pool level of 538 ft (Fig. 17).

The differences in EPM balance from high to low lake stage is caused by statistically significant differences in concentrations of the forementioned divalent cations and the bicarbonate and sulfate anions. At stage 540.5 ft on February 27, concentrations of Ca^{+2}, Mg^{+2}, HCO_3^{-1}, and SO_4^{-2} were 5.55 $\pm$ 0.30, 22.0 $\pm$ 2.52, and 25.2 $\pm$ 0.97 mg/l, respectively. At stage 536.6 ft on September 21, the values were 14.2 $\pm$ 0.25, 5.3 $\pm$ 0.11, 29.1 $\pm$ 1.71, and 29.2 $\pm$ 0.51 mg/l, respectively. These means and standard deviations represent all samples in the middle and lower basins to depths of <10 ft. The numbers of samples are given in Fig. 17. The other ions in the balances (Na^{+1}, K^{+1}, and Cl^{-1}) did not differ significantly. It should be noted that these ion concentrations are very low compared to those of other surface waters in southern Indiana which are generally "hard" waters. Monroe Reservoir is a "soft" water lake.

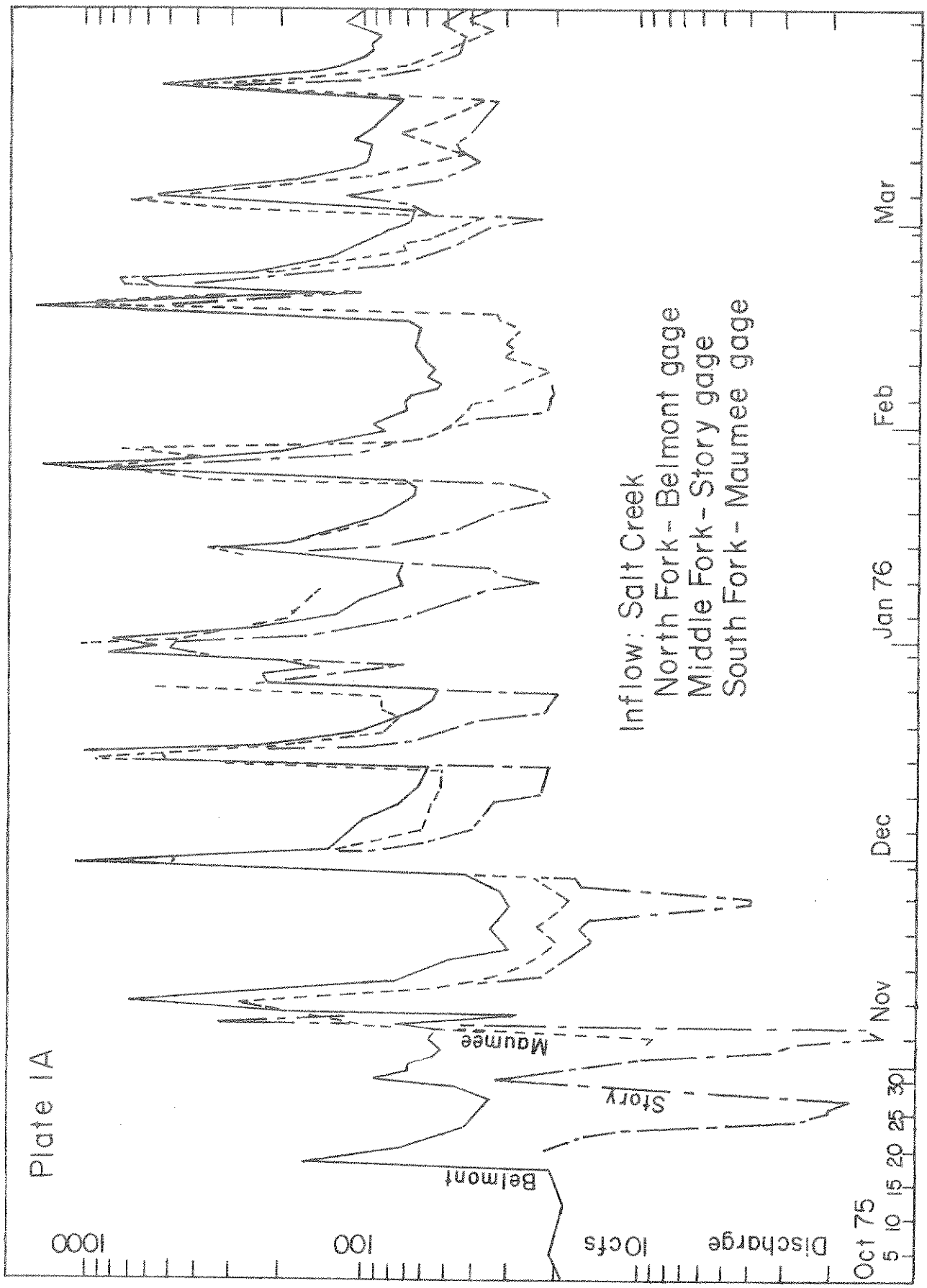
Plate IA
Inflow: Salt Creek
North Fork - Belmont gage
Middle Fork - Story gage
South Fork - Maumee gage
Discharge 10cfs
1000
100
Belmont
Story
Maumee
Oct 75
5
10
15
20
25
30
Nov
Dec
Jan 76
Feb
Mar

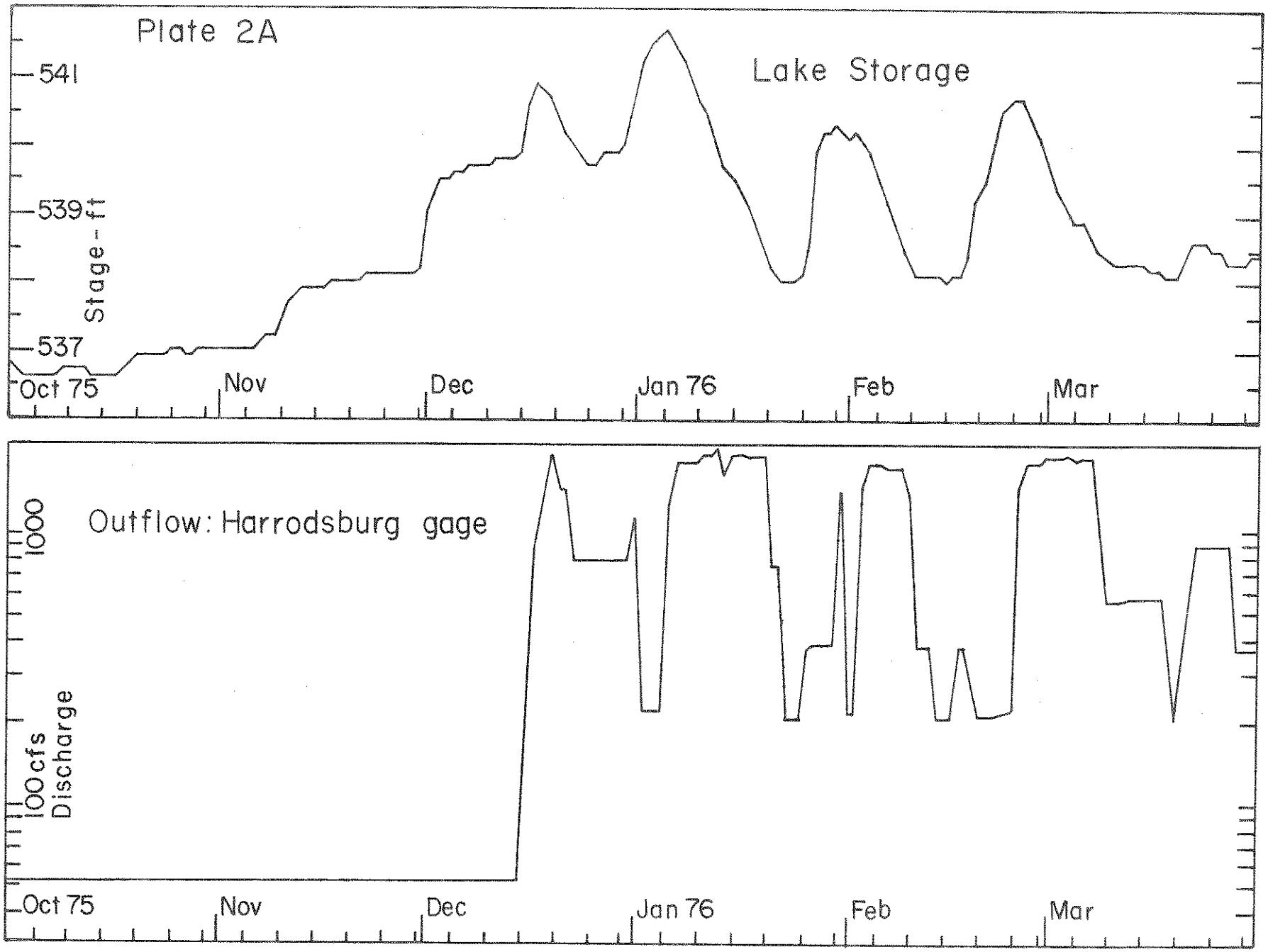
Plate 2A
Lake Storage
541
539
537
Stage - ft
Oct 75
Nov
Dec
Jan 76
Feb
Mar
Outflow: Harrodsburg gage
1000
100 cfs
Discharge
Oct 75
Nov
Dec
Jan 76
Feb
Mar

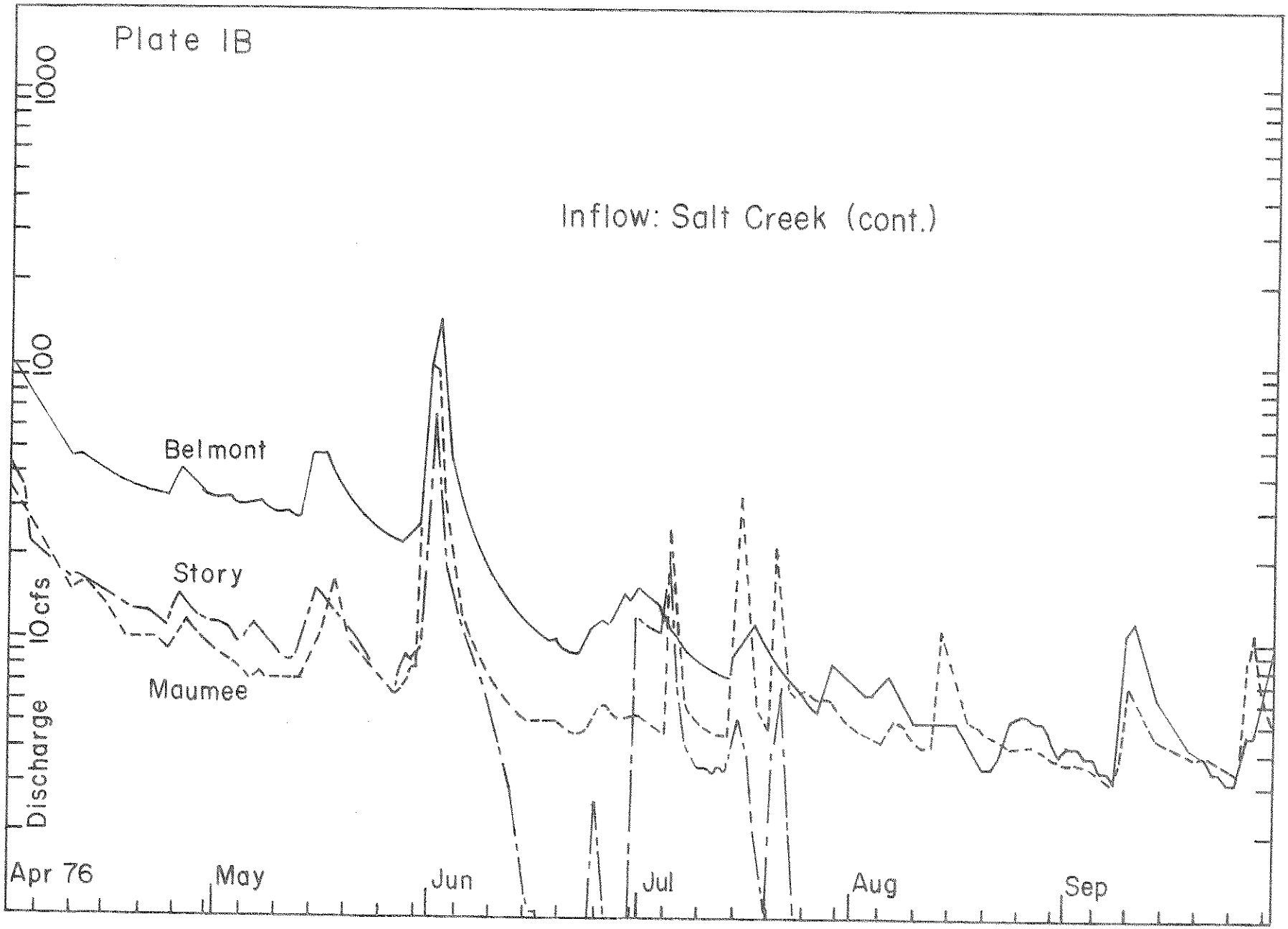
Plate IB
Inflow: Salt Creek (cont.)
Discharge 10cfs
1000
100
Belmont
Story
Maumee
Apr 76
May
Jun
Jul
Aug
Sep

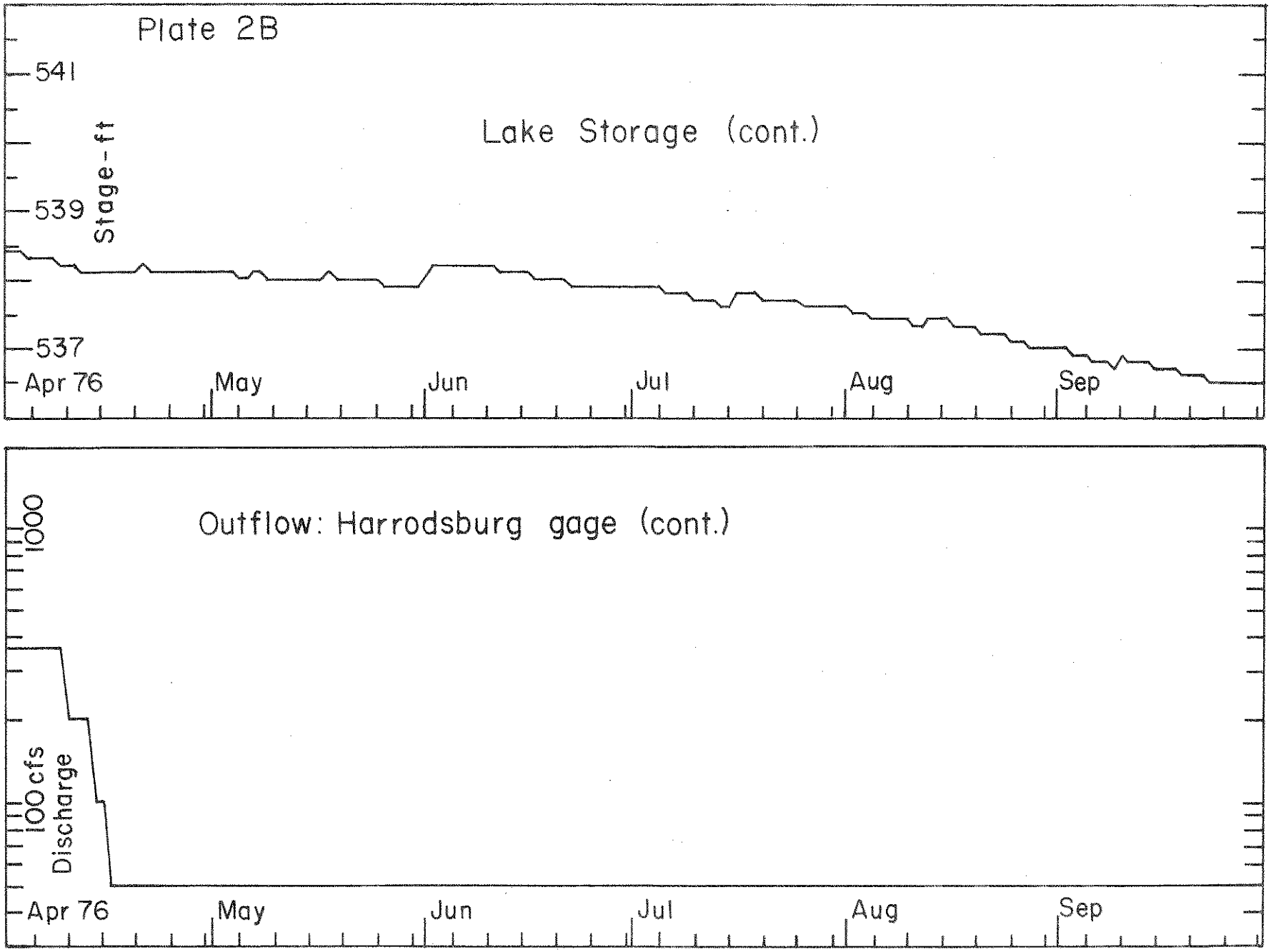
Plate 2B
541
539
537
Stage-ft
Lake Storage (cont.)
Apr 76
May
Jun
Jul
Aug
Sep
1000
100 cfs
Discharge
Outflow: Harrodsburg gage (cont.)
Apr 76
May
Jun
Jul
Aug
Sep

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Part II

NUTRIENT RELATIONS, MONROE RESERVOIR, INDIANA

W.Y.B. Chang and D. G. Frey

INTRODUCTION

Lake Monroe was originally built for flood control in southern Indiana. At present, it serves as a primary water resource for surrounding regions such as Bloomington and Ellettsville. In recent times, there has been excessive local development on the lake shore, increase of recreational uses of the major part of the reservoir, and direct sewage effluent input into the lake. As such input of nutrients can accelerate the process of eutrophication, this research has concentrated on the factors that control water quality in the lake (Frey, 1974). First, it is necessary to understand how the system functions and how green plants (phytoplankton in particular) respond to environmental variables, especially nutrient enrichment.

Studies were undertaken to determine the annual production rates and the trophic level of the lake to serve as a basis for interpreting the subsequent nutrient enrichment experiments. The study attempts to resolve the question of which nutrients are limiting algal production and under which conditions.

METHODS

Primary productivity in aquatic environments is measured most accurately by techniques that monitor the flux of metabolically labile molecules, especially oxygen and carbon dioxide. The most common and accurate technique currently in use involves the differential metabolism in transparent and darkened bottles of C-14 labeled carbon dioxide.

Incubation of water samples from station 4 above the causeway in Lake Monroe was made in situ at weekly intervals during the more productive months of 1975 (April through September), at biweekly intervals during the remainder of that year and through August of 1976. Pyrex glass-stoppered bottles of 125 ml$^{+5\%}$ volume were used in the incubation (Lewis, 1972). The bottles were flushed and filled in the field from a 2-liter plastic Van Dorn sampler. Samples of water were collected at meter intervals from the surface to 6 m which is the normal lower limit of the trophogenic zone in this lake. Four bottles were filled from each depth. One served as a control. To the others were added stopwise increments of nitrogen (as nitrate) and phosphorus (as phosphate) singly or in combination.

Stock solutions were prepared containing 0.25 mgN/ml as $NaNO_3$ and 0.05 mgP/ml as KH_2PO_4. On each date the actual concentrations of nutrients added varied with the season of the year and the concentrations of the nutrients in the water. Bottles designated A had the lowest concentrations of added nutrients, those designated C the highest concentrations.

A partitioned box with light-excluding lids for the bottles protected the samples from light damage while they were on deck. A dark bottle was also filled from the depths 0m, 3m, and 6m with the label of 1A, 4B and 7C.

The C-14 inoculum consisted of a sterile and ampulated Na_2CO_3 water solution with an activity of 2.00μCi per ml. As the activity of the inoculum was determined in gas phase, it can be regarded as accurate (Lewis, 1972). One ml of the solution was added to each of the samples with an automatic syringe.

After inoculation the samples were sealed and shaken immediately to mix the C-14 label, then were suspended at the depths from which they had been collected. The suspension device consisted of a circular steel bar with a diameter of about 1.5 ft, kept at the surface by 3 floats. Attached to a rope suspended from this device were plexiglas plates to which were attached open-ended conduit clips. The latter kept the bottles in horizontal position at the selected depths. Horizontal bottle suspension is advantageous and the conduit clips have the additional merit of reducing handling time on deck (Ohle, 1958; Elster and Motsch, 1966; Lewis, 1972). Care was exerted to avoid shading by the suspension device, but nevertheless the surface samples were often shaded from direct sunlight by the suspension floats. Wave action no doubt helped to keep the plankton in suspension, and hence it is doubtful that settling of a majority of the plankton was significant during the brief incubation period. The incubation periods never exceeded 6 hrs, which is adequate for significant uptake of C-14 and yet sufficiently brief to minimize

bottle effects (Vollenweider and Nauwerck, 1961). Upon removal the samples were placed in a light-tight box and then were taken immediately to the laboratory for filtration.

In the laboratory, 50 ml subsamples of each bottle were filtered through millipore membranes having a porosity of 0.45 ± 0.02μm (HA: Millipore Filter Corp., Bedford, Mass.). Vacuum pressures were never allowed to exceed 18 $HgCm^2$ and generally were in the range of 10 - 16 $HgCm^2$. The wet filters were transferred to scintillation vials containing 10 ml of dioxane cocktail solution (Schindler, 1966), capped, and shaken vigorously. At times, a strong coloration was apparent in the vial due to dense phytoplankton biomass. The radioactivity was measured after 2 to 3 hrs on either an LS-100 or an LS-232 scintillation counter. The vials were individually quench-corrected by the Channels-ratio method. A significant loss of label through Millipore HA filters has been found by Schindler and Holmgren (1971), who suggested a correction procedure based on an extrapolation to zero volume. This procedure was tried for some of the incubations, but it did not show any significant loss of label through the filter. The same finding was also reported by Lewis (1972).

The dpm figures corrected for quenching were then converted to mg C/m^3 assimilated by Vollenweider's (1970) procedure. The available CO_2 was estimated from the tables of Rebzdorf (1972), using pH, temperature, and the alkalinity content of water from the same depth as the incubated samples. The customary isotopic discrimination factor of 1.06 was also used in the calculation (Steemann Nielson, 1952; Vollenweider, 1970). The productivity

of the incubation period was expanded to the productivity for the entire day by the ratio of the solar radiation for the entire day to that portion received during the incubation period, as determined by planimetry from pyrheliometer records. Comparison between the productivity in the bottles with various nutrient enrichments and in the control are made using Fisher's distribution-free sign test. The detailed procedure of the method is included in the Appendix.

The pH values were determined electrometrically (Corning pH model 7 with a Bradley James combination electrode). Alkalinity (methyl orange alkalinity) was measured by adding 0.01N sulphuric acid to a pH-determined end point of 4.4. Dissolved oxygen was determined by the unmodified Winkler procedure.

Nutrient concentrations were measured on water samples from the same depth-intervals at which productivity samples were taken. Nitrogen (nitrate, nitrite, and ammonia) and soluble reactive phosphorus determinations were made on samples filtered through HA millipore membranes. Glassware used for phosphorus determinations was acid-washed and rinsed in double-distilled water just prior to use. Total phosphorus after persulfate digestion and reactive phosphorus were determined by the extraction method of Golterman and Clymo (1969). Optical density was read in a 10-cm cell in a Beckman DU spectrophotometer at a wavelength of 885 mμ. NO_3-N was determined by the column reduction method during spring to late fall when concentrations in the lake were low and by the powder pillow technique in winter when concentrations were much

higher. NH_4-N and NO_2-N were determined following the method of Stainton, Capel, and Armstrong (1974). Reactive silicate was determined using the procedure of Strickland and Parsons (1972).

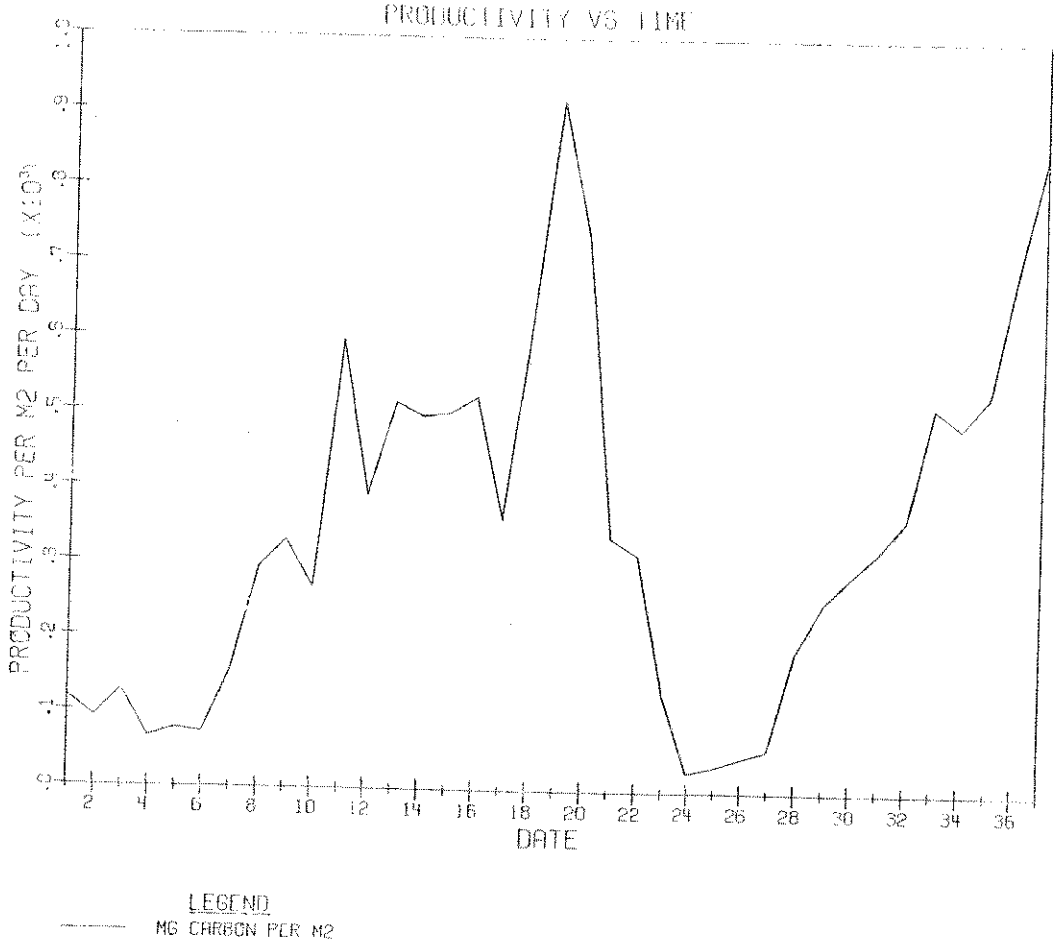
PRODUCTIVITY AND TROPHIC TYPE

The integrated photosynthesis of the phytoplankton at Station 4 in Lake Monroe exhibited relatively sustained although moderate levels throughout the warmer period of the year, with maximum in September 1975 and August 1976 (Fig. 1). Productivity during the period October through April or May was markedly less. The seasonal productivity curve followed the trend of incident solar radiation in a general way (Fig. 2).

The daily mean primary productivity of the upper basin over the period May 1975 through August 1976 was 343 mg $C/m^2/day$, within an observed range of 26 mg $C/m^2/day$ (November 24, 1975) to 917 mg $C/m^2/day$ (September 1, 1975). Photosynthesis accomplished during the period from November 1975 through March 1976 constituted only 3.95% of the total annual productivity. The daily mean value for this same period was 40 mg $C/m^2/day$.

Figures 3 to 7 are selected examples from the entire series of 37 dates that illustrate the range of depth profiles encountered. The profile of February 8, 1976 was typical of the winter period (Fig. 3). The productivity curves of May 19, 1975 (Fig. 4) and October 13, 1975 (Fig. 5), represent the type of variation found in the spring and fall. Figures 6 and 7 represent the summers of 1975 and 1976, respectively. No photo-inhibition was observed on the dates sampled in the late summer of 1975, but there were instances of inhibition in July and August 1976. This difference may have resulted from the dominant species being different in the two years--Melosira in 1975 and Cyclotella in 1976. The

Figure 1. The intergrated production of the phytoplankton per m^2 in lake Monroe in the study period.



1 - May 5, 1975
2 - May 12, 1975
3 - May 15, 1975
4 - May 19, 1975
5 - May 22, 1975
6 - May 26, 1975
7 - June 9, 1975
8 - June 23, 1975
9 - June 20, 1975
10- July 2,1975
11- July 7, 1975
12- July 9, 1975
13- July 16, 1975
14- July 23, 1975
15- July 30, 1975
16- Aug. 3, 1975
17- Aug. 13, 1975
18- Aug. 18, 1975
19- Sept. 1,1975
20- Sept. 15, 1975
21- Sept. 29, 1975
22- Octo. 13, 1975
23- Octo. 27, 1975
24- Nov. 24, 1975
25- Dec. 8, 1975
26- Feb. 9, 1976
27- Mar. 3, 1976
28- Mar. 19, 1976
29- Apr. 7, 1976
30- Apr. 21, 1976
31- May 24, 1976
32- June 7, 1976
33- June 24,1976
34- July 6, 1976
35- July 20, 1976
36- Aug. 3, 1976
37- Aug. 16, 1976

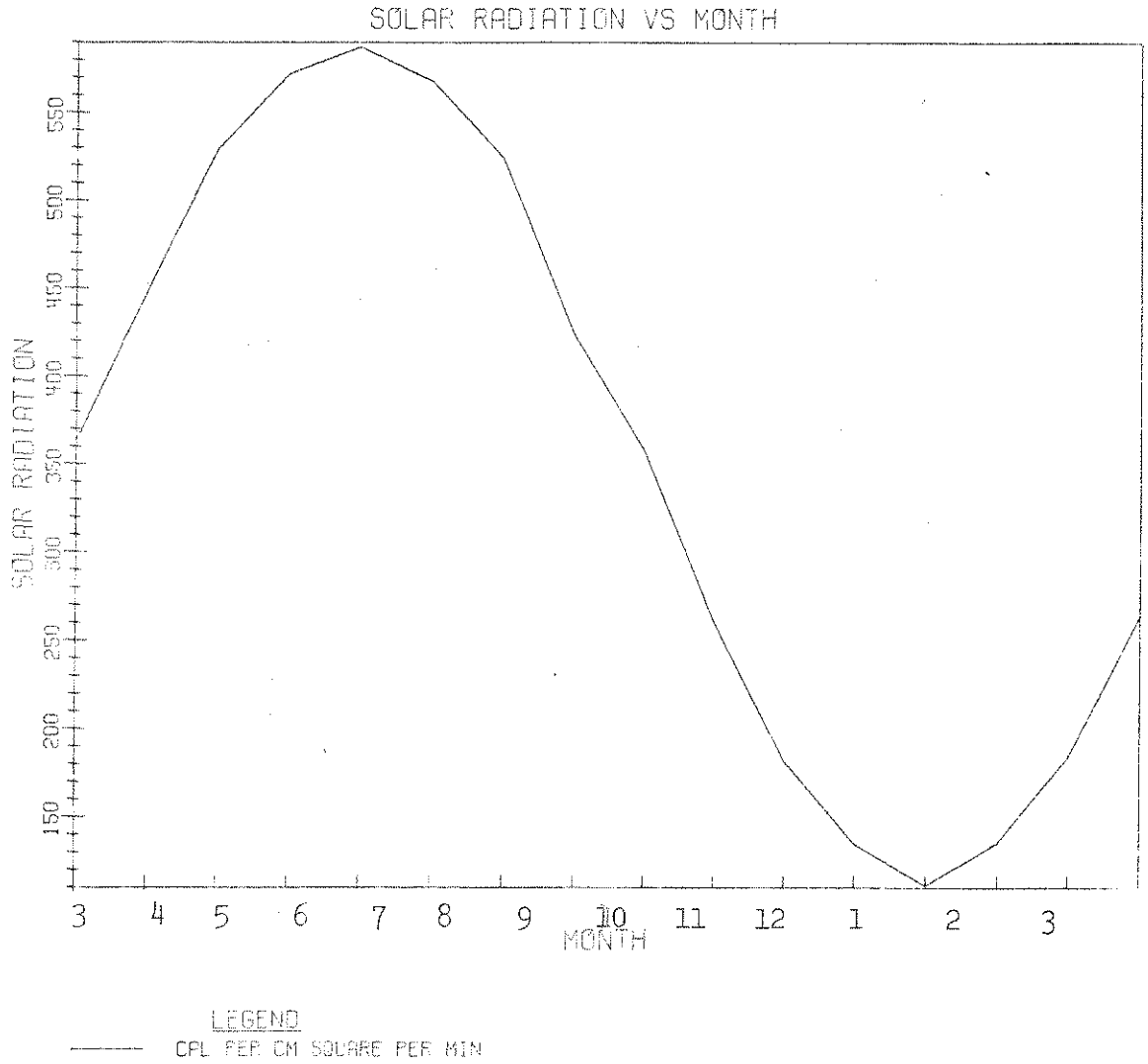


Figure 2 The monthly incident solar radiation based on List's (1951) table, corrected for the latitude of Lake Monroe.

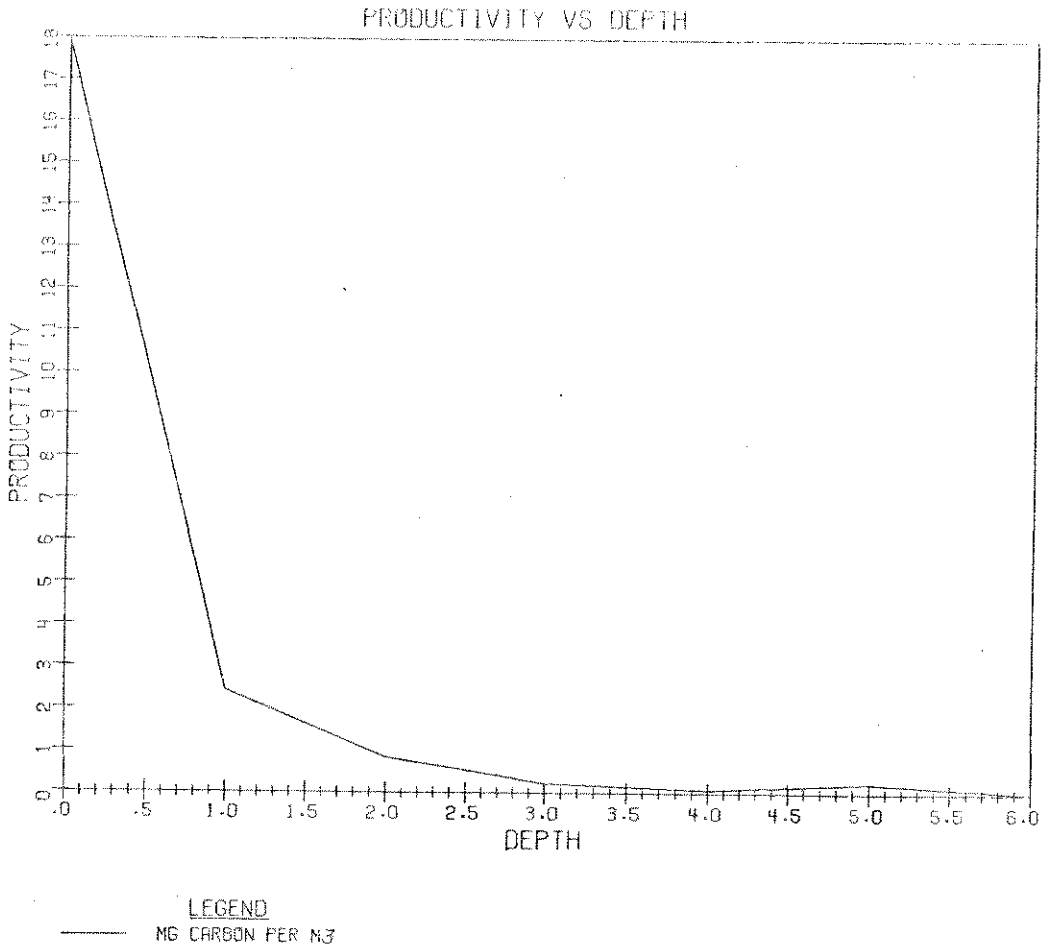


Figure 3 The productivity-depth profile of February 8, 1976

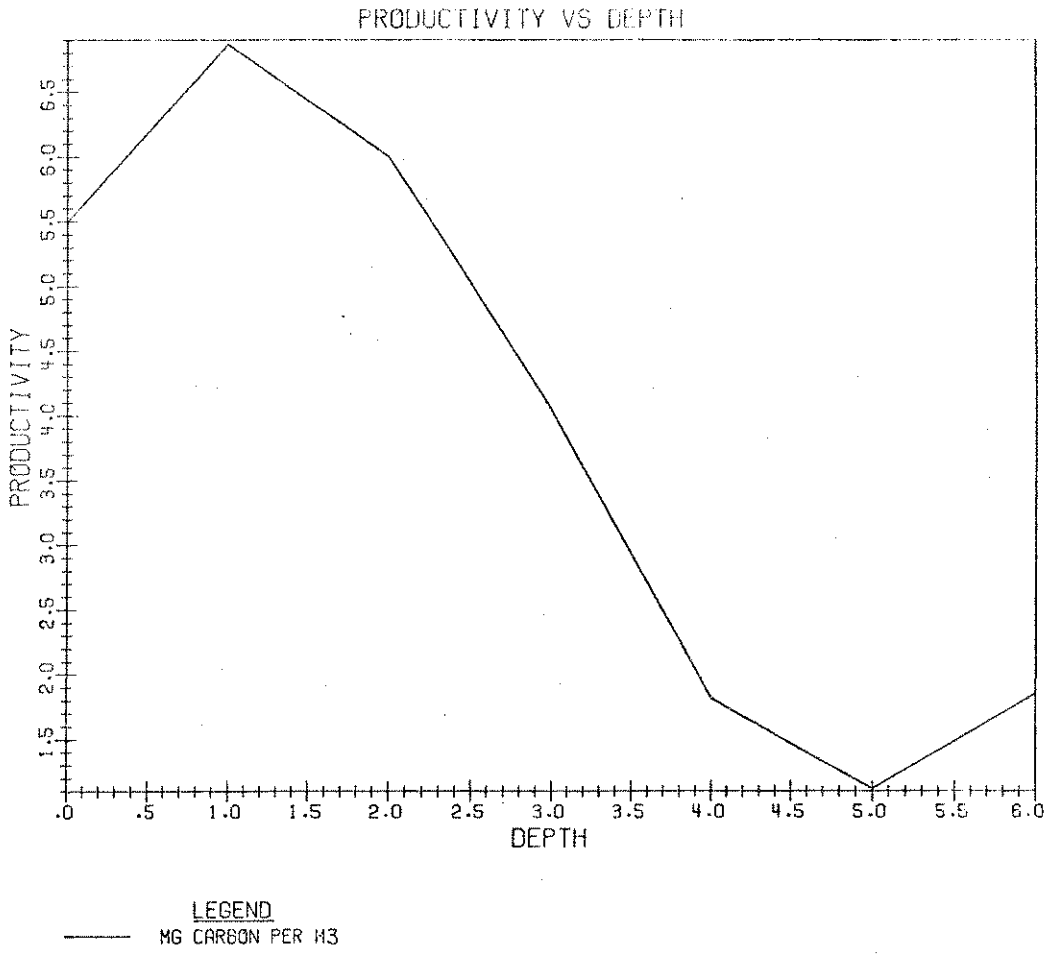


Figure 4 The productivity-depth profile of May 19, 1975

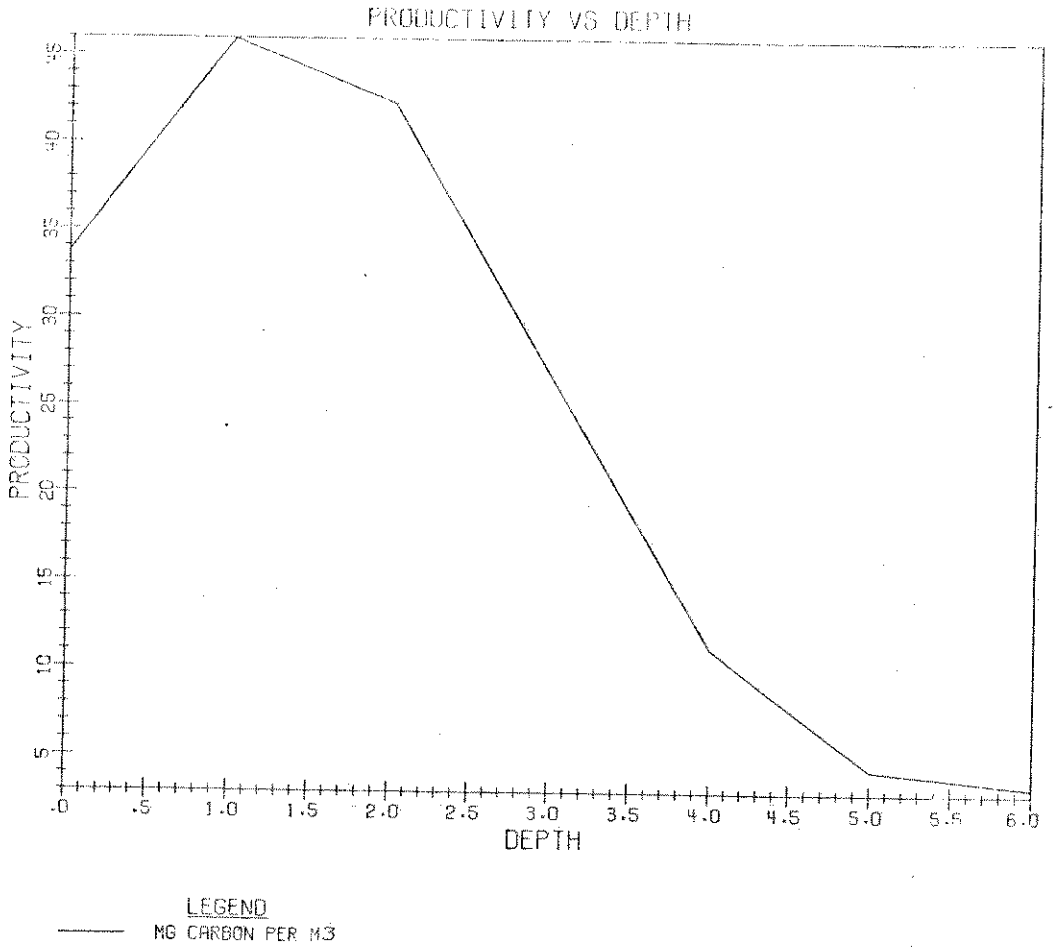


Figure 5 The productivity-depth profile of October 13, 1975

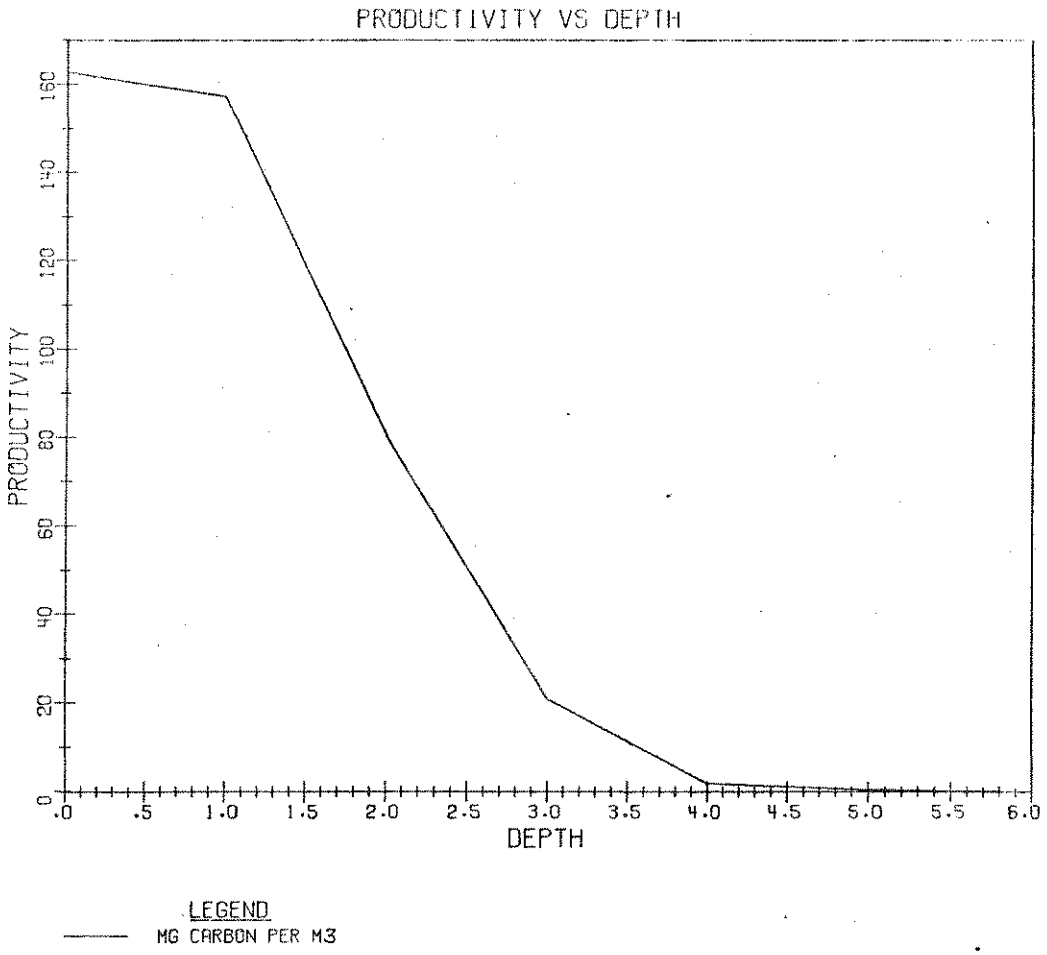


Figure 6 The productivity-depth profile of September 1, 1975

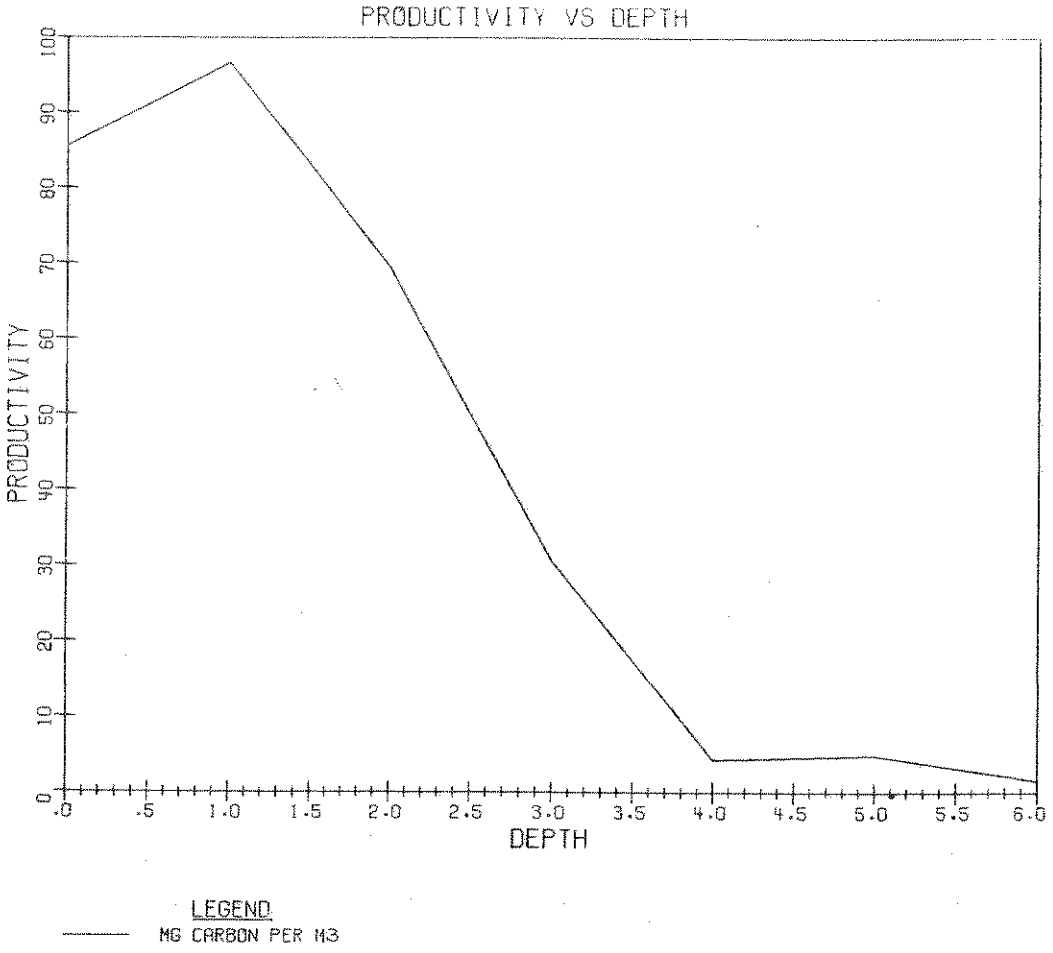


Figure 7 The productivity-depth profile of August 3, 1976 in lake Monroe.

unusually low winter production in 1976 is attributed to high-water levels and consequent high levels of turbidity, which would restrict the thickness of the trophogenic zone. Thus, productivity occurred only at the very surface of the lake, as on February 8, 1976 (Fig. 3).

In order to assess the effect of nutrient enrichment, it is desirable to estimate the trophic level of the lake in relation to other lakes that have been studied. This can be done in several ways, but measurements of organic content and of primary productivity are the two most convenient and reliable methods. The method proposed by Rodhe (1958) uses the ratio between maximal photosynthesis per cubic meter (V) and total photosynthesis beneath a square meter of lake surface (A)--the V/A ratio. This is based on the great differences in productivity-depth profiles in lakes of widely different trophic status. For instance, if a lake is hypereutrophic, most of the production will be concentrated near the surface due to the buildup of large algal populations which would greatly reduce light penetration to deeper strata. Under these conditions V would approach A, and hence the V/A ratio would approach 1. Such lakes are light limited. Conversely, in an oligotrophic lake deeper layers are not shaded by large populations of phytoplankton, and hence production extends to greater depths and exhibits a less-pronounced maximum. The V/A ratio will be low, because nutrients not light are limiting production. If the lake is sufficiently deep, the curves for light penetration and primary productivity will closely parallel one another.

For the lakes he studied in Sweden, Rodhe (1958) determined that the eutrophic lakes, Erken and Gorvalin, have V/A ratios of 0.30 and 0.38 respectively, and that the oligotrophic lakes, Kultsjon and Ransaren, have ratios of 0.20 and 0.18, respectively. The V/A ratios in Lake Monroe ranged from 0.20 to 0.38, with a mean of 0.295. At face value these ratios would suggest that Lake Monroe is upper-mesotrophic compared with the Swedish lakes. However, the mean ratio is distorted toward higher values, and hence is deceptive, by the high levels of inorganic turbidity in spring and early summer, which would concentrate photosynthesis toward the surface for non-biological reasons.

Rodhe (1969) also attempted to set up ranges of daily productivity in relation to trophic status. During June through July the oligotrophic lakes Ransarin and Kultsjon had mean rates of photosynthesis per square meter of lake surface of about 50 mg $C/m^2/day$, with maximum values between 100 and 150. The eutrophic lakes, Erken (Sweden) and Esrom (Denmark), had primary productions of about 500 and 500 to 1000 $mg/m^2/day$, respectively. For lakes in Denmark and Sweden that are heavily fertilized by domestic and industrial pollution, productivity in spring and autumn was as high as 1500 to 3000 mg $C/m^2/day$, some readings even as high as 600 mg $C/m^2/day$.

These measurements provide a rough set of productivity standards against which other lakes can be compared. Lakes in the range of 50 - 150 mg $C/m^2/day$ are oligotrophic, 500 - 1000 mg $C/m^2/day$ eutrophic, and 1500 - 3000 mg $C/m^2/day$ hypereutrophic or polluted.

The mean daily productivity of Monroe lake over the year was 343 mg C/m^2, with individual measurements ranging from 26

to 917 mg C/m /day. These values likewise suggest that Lake Monroe is upper-mesotrophic in its general trophic condition.

These findings are also confirmed by the vertical extinction coefficients and the transparency. The annual mean extinction coefficient, excluding winter and spring when high light extinction results from inorganic turbidity not from algal production, was 1.06, with a range of 0.64 to 1.88.

The Secchi disc transparency likewise excluding measurements in winter and spring, averaged 1.96 m, with a range of 0.9 to 3.2 m. Such figures are suggested by Wetzel (1966) as being typical of lakes with intermediate productivity.

THE SEARCH FOR LIMITING FACTORS

Various inorganic nutrients dissolved in the water are necessary for the survival and growth of photosynthetic algae. Unlike artificially prepared culture media in which the nutrients are present roughly in proportion to their needs by the algae, in most waters, there is a disproportion between the composition of the minerals present and the demands for organic growth. Single ions such as Ca^{++} and HCO^{-}_{3} are often present in amounts far in excess of the requirements, while others, such as phosphate ions, are usually present in disproportionately small quantities (Ruttner, 1967). Thus the plants cannot utilize an abundant ion because they suffer from inadequate supply of some other substance. The growth of photosynthetic organism, in particular algae, is therefore limited by the nutrient present in the least amount in relation to needs. This relationship is the well-known law of the minimum, which in the current context states that primary productivity is limited at any given time by the nutrient present in water in the least amount in relation to its needs by the organism. This is the so-called limiting factor. For example, if a rich supply of nitrogen will increase productivity only when phosphorus is increased, it is obvious that phosphorus is the limiting factor and not nitrogen.

In the present investigation two different methods were used to identify and quantify limiting nutrients. First, through chemical analysis and especially the changes that occur over the 24-hour period in response to the changing importance of photosynthesis and respiration, the nutrient elements that change most drastically

in concentration can be identified. Second, the stimulating effect of nutrients added incrementally either singly or in combination is measured by radiocarbon uptake and compared with the photosynthetic activity of the algae in lake water without the addition of nutrients.

Approach I

Of the various elements that are known to be essential in plant nutrition, relatively few become limiting, because their supply is generally greater than their demand. On June 9, 1975 chemical analyses of the water were made at 4-hour intervals. Soluble reactive phosphorus and nitrate were the only nutrients that decreased in concentration during the daylight period coincident with the growth of phytoplankton. For instance, soluble reactive phosphate decreased from 4.10 µg N/l at 6:30 a.m. to 1.6 µg/l at 2:30 p.m., whereas total phosphate (unfiltered) increased from 18.2 µg N/l to 20.3 µg N/l as was expected (Fig. 8). The latter increase is attributed to the incorporation of soluble reactive phosphate by algae. Nitrate decreased from 109.2 µg N/l at 6:30 a.m. to 41.2 µg N/l at 2:30 p.m. (Fig. 9), maintaining a N/P ratio of roughly 26. The data suggested that phosphate and nitrate played a significant role in algal growth.

A further study of concentrations of nutrients was made with special attantion to soluble reactive phosphate and nitrate. Two forms of phosphate were analyzed chemically: soluble reactive phosphate (SRP), which is the form utilized by phytoplankton as a nutrient, and total hydrolyzable phosphorus (TP) in unfiltered samples. The latter includes not only polyphosphates and the

Figure 8 PHOSPHATE CHANGE IN THE TROPHOGENIC ZONE ON JUNE 9, 1975
SAMPLES ARE COLLECTED AT THREE DIFFERENT TIME IN THE DAY

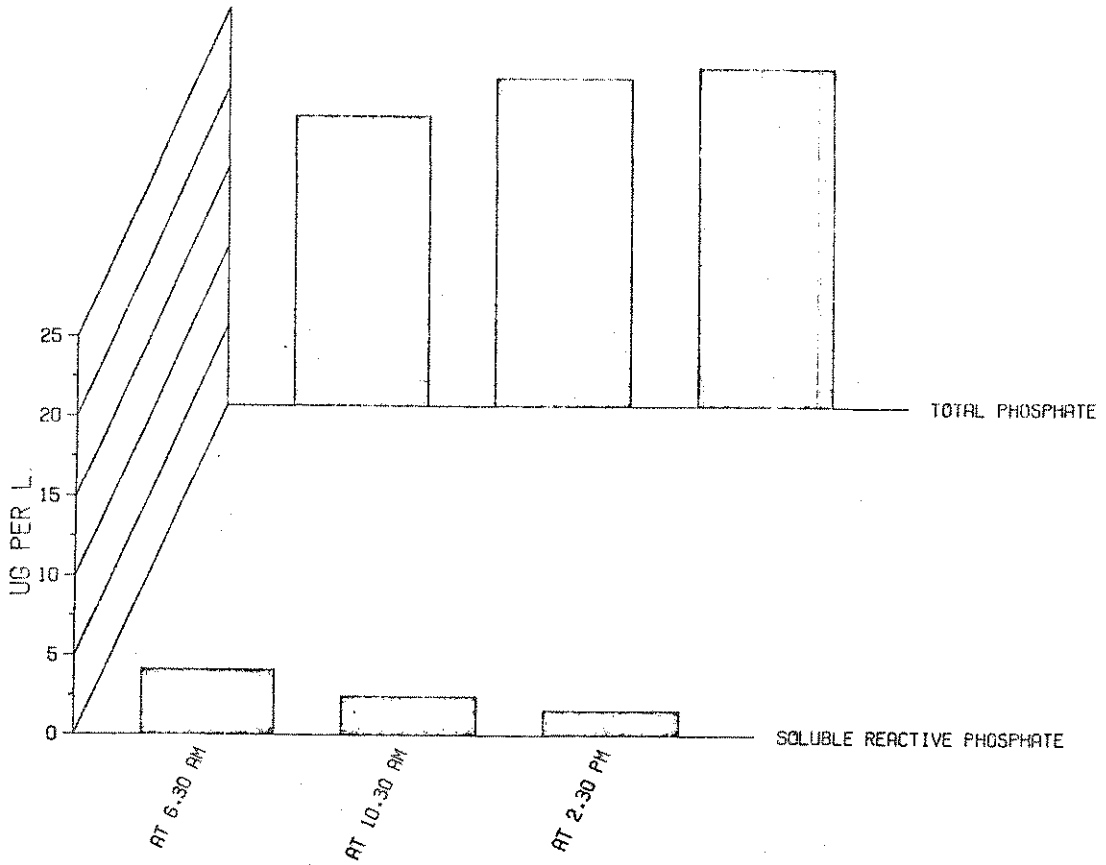
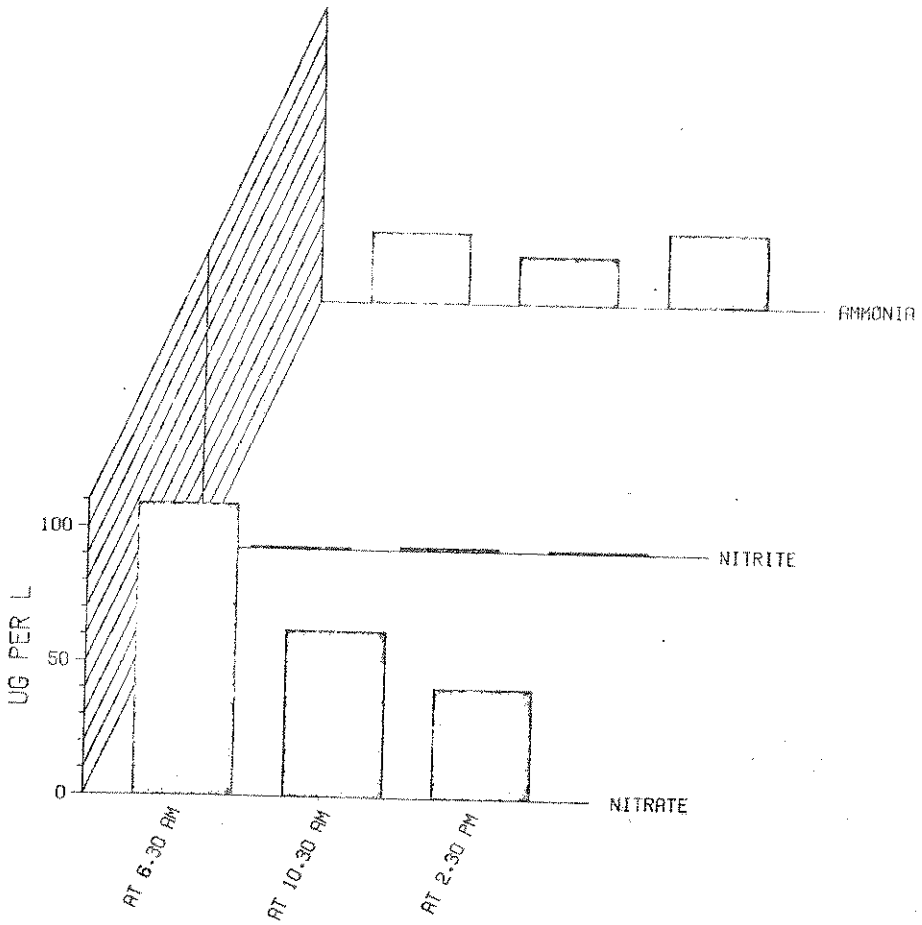


Figure 9 NITROGEN CHANGE IN THE EUPHOTIC ZONE ON JUNE 9, 1975
SAMPLES ARE COLLECTED AT THREE DIFFERENT TIME IN THE DAY



phosphorus associated with soluble organic compounds but also the phosphorus of living organisms and that associated with non-living particles.

Both forms of phosphorus occurs in low concentrations in Lake Monroe (Table 1). The highest concentration of SRP in the trophogenic zone at any time at any station for the period of May 1975 to August 1976 was only 15.1 μg/l. Most of the time the concentration was no higher than 2μg/l. During summer and autumn the concentration in the trophogenic zone often was below the detection limit (0.1 μg/l) of the Beckman DU with a 10-cm cell. The highest concentration of SRP in the trophogenic zone was observed at all stations during May 1975 and February and March 1976.

The concentrations of total phosphorus were necessarily higher than those of SRP. The highest concentration was 143.2 μg/l on February 18, 1976. During summer, SRP reached a minimum concentration of 10 - 15 μg/l at the station above the causeway, and remained this low the rest of the season.

The three forms of inorganic nitrogen in water are ammonia, nitrite, and nitrate. Ammonia is an endproduct of a microbial activity. It can be oxidized through nitrite to nitrate by specialized bacteria, or in reverse nitrate can be reduced to ammonia by other bacteria, depending on environmental conditions. Nitrite, being a transitional form, rarely occurs in any appreciable concentration in unpolluted water. Phytoplankton can utilize both ammonia and nitrate as sources of nitrogen, some groups of algae preferring nitrate and other groups preferring ammonia (Hutchinson, 1967; Frey, 1976). However, nitrate is generally considered the

more important source of nitrogen in phytoplankton ecology (Frey, 1976), and it exhibited a direct reduction of concentration with the growth of algae in Lake Monroe (Fig. 10).

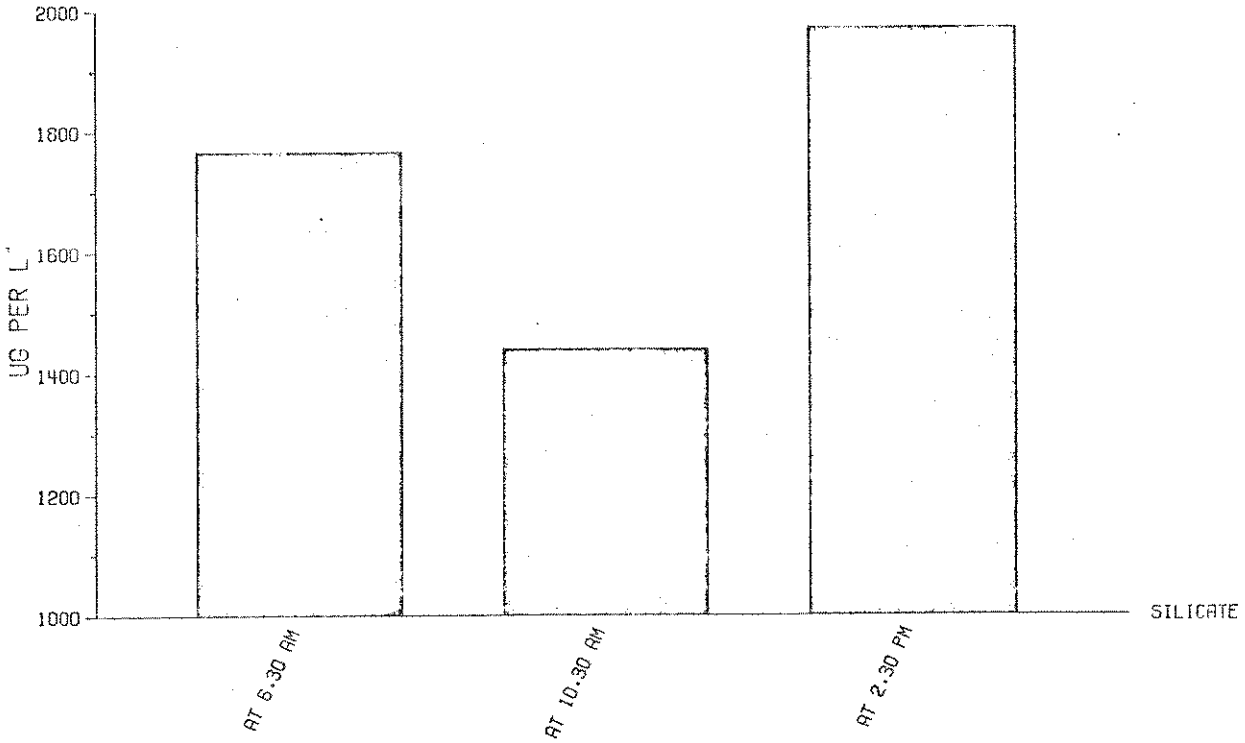
TABLE 1. Nutrient Concentrations in Lake Monroe in μg N or P/l During the Study Period May 1975 to August 1976

	Mean (μg/l)	Range (μg/l)
Total hydrolyzable phosphorus	23.1	1.4 - 143
Soluble reactive phosphate	1.6	0 - 15.1
Ammonia	17.7	2 - 47.8
Nitrite	1.8	0.05 - 6.6
Nitrate	37.6	1.4 - 223
Soluble reactive silicate	1442	35 - 3825

Although inorganic nitrogen was present in the lake at all time, there were pronounced seasonal changes in concentration. Nitrate concentrations were generally low in summer and higher in winter. Nitrite concentrations generally were about one order of magnitude smaller than nitrate during the entire experimental period. The concentration of ammonia rarely fell below 5 μg/l in the trophogenic zone. During summer stratification the concentration of ammonia at 5 m and deeper was much greater than at the surface, associated with the greatly reduced oxygen concentrations at these depths.

Figure 10 SILICATE CHANGE IN THE TROPHOGENIC ZONE ON JUNE 9, 1975

SAMPLES ARE COLLECTED AT THREE DIFFERENT TIME IN THE DAY



The concentration of inorganic nitrogen in the forms of nitrate and ammonia during the year was always considerably greater than that of SRP. The ratio between nitrogen in the form of nitrate and ammonia and phosphorus as SRP was 35 to 1 on an atomic basis, 16 to 1 on a weight basis. In summer and autumn, when the SRP shortage was most acute, the ratios are considerably greater than these.

This indicates that the limiting nutrient is phosphorus rather than nitrogen, because in relation to phosphorus all other nutrients, particularly nitrogen, are present in excess amounts.

Approach II

In this approach the stimulation of photosynthesis by incremental additions of nutrients was measured in situ over exposure periods of 5 - 6 hours. Of 39 independent experiments, 9 runs yielded significantly greater (5% or 1% level) photosynthesis from the addition of phosphorus (7 cases) or EDTA (2 cases). Nitrate additions had no effect. (See Figs. 11 - 17 and Tables 2, 3.) A significant increase in growth from the addition of phosphate occurred most frequently in the spring months when the phytoplankton biomass was high. Of the 7 cases that exhibited significant increases, 6 occurred in the spring of 1975 and 1976.

Nitrogen as nitrate was not of major importance in algal production relative to phosphorus. None of the increases observed were due to the addition of nitrate alone. On May 26, 1975 when N and P were added together, the results were indistinguishable from those of other experiments in which only P was added. Furthermore, on April 21, 1976 when 1 ml of P was added to one set of bottles and 3 ml

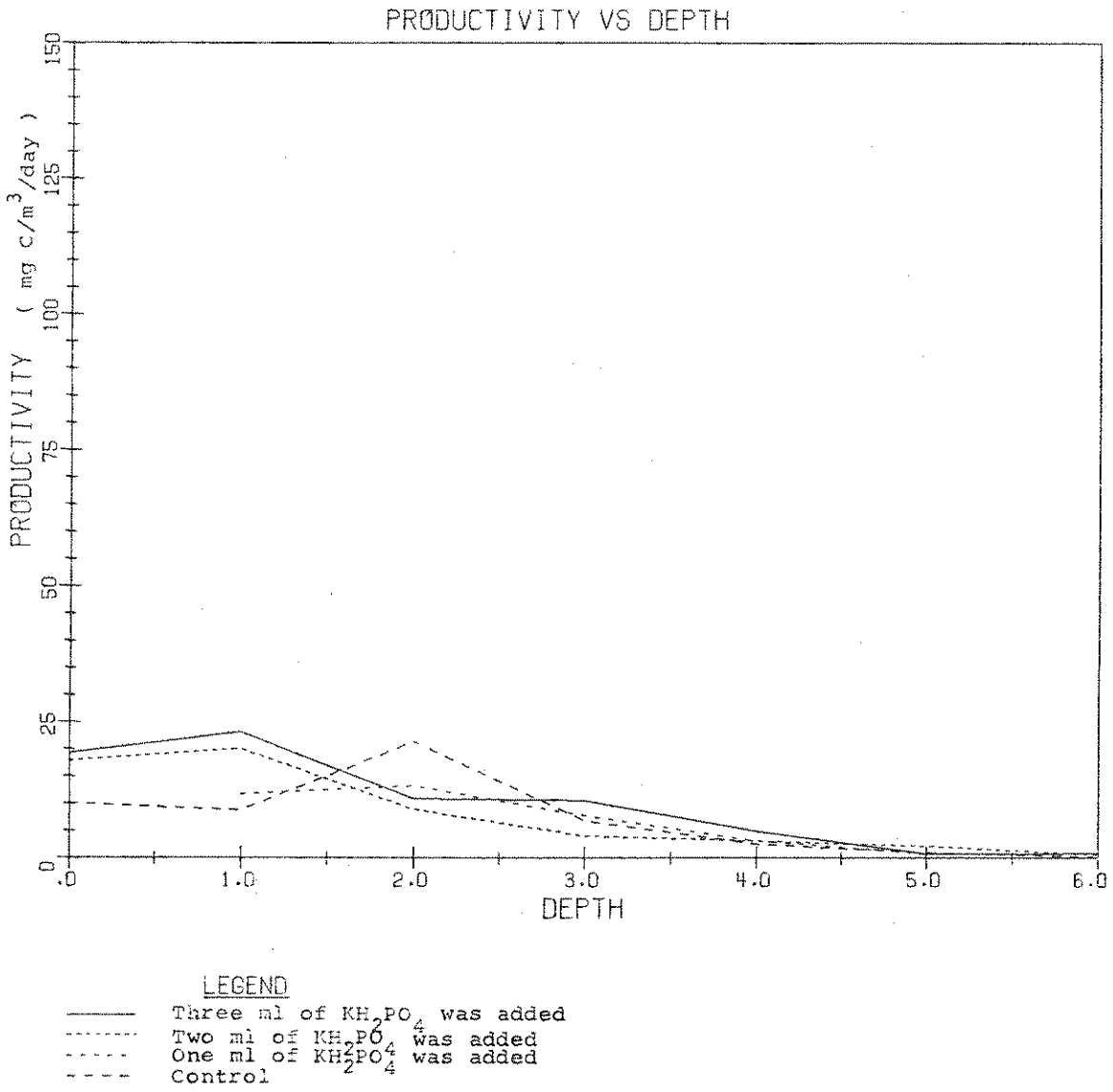


Figure 11 Response of phytoplankton growth to phosphate enrichment in insitu bioassay cultures as measured by carbon-14 assimilation on May 5, 1975 in lake Monroe, Indiana.

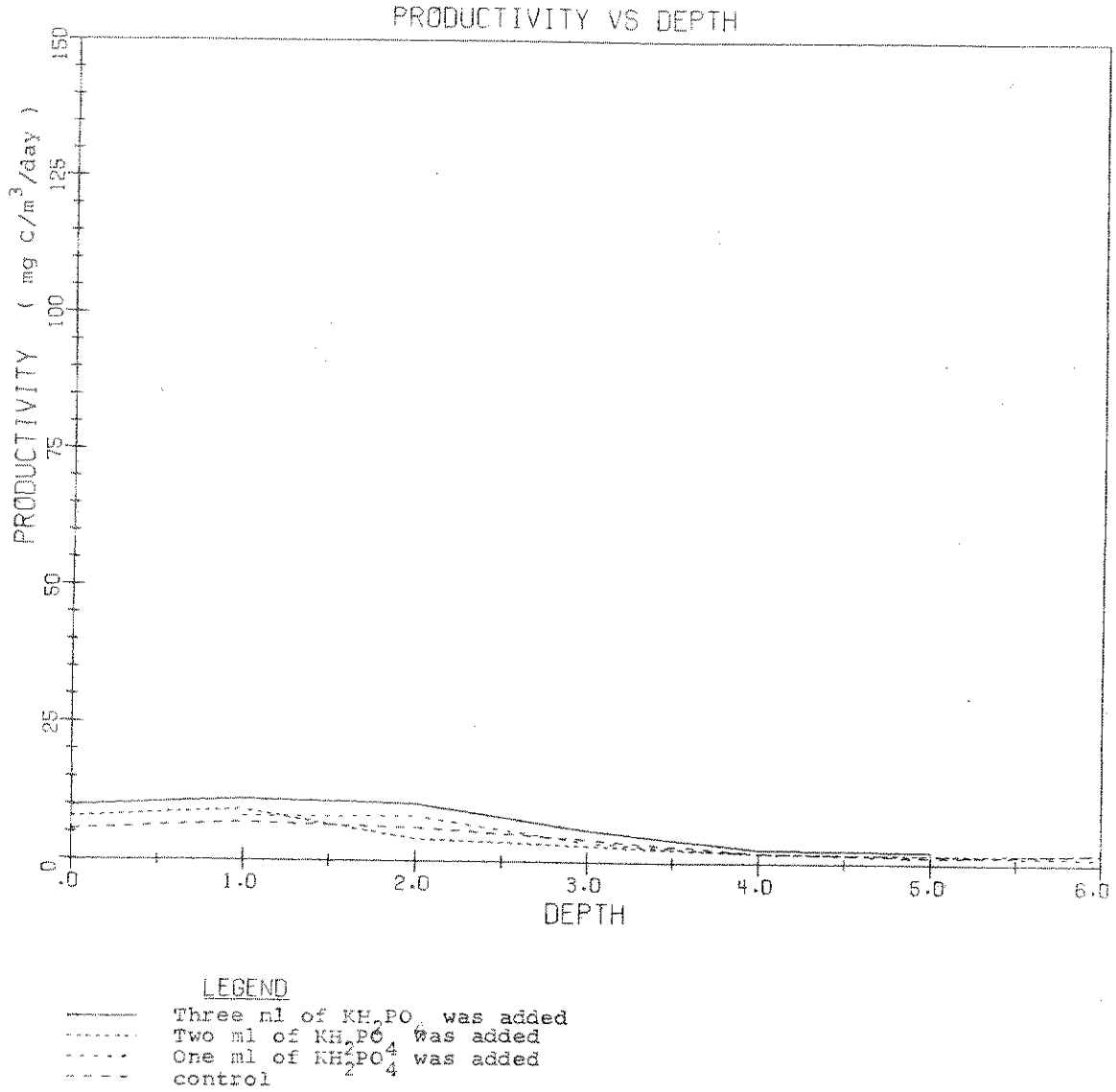


Figure 17 Response of phytoplankton growth to phosphate enrichment in <u>in situ</u> bioassay cultures as measured by carbon-14 assimilation on May 19, 1975 in lake Monroe, Indiana.

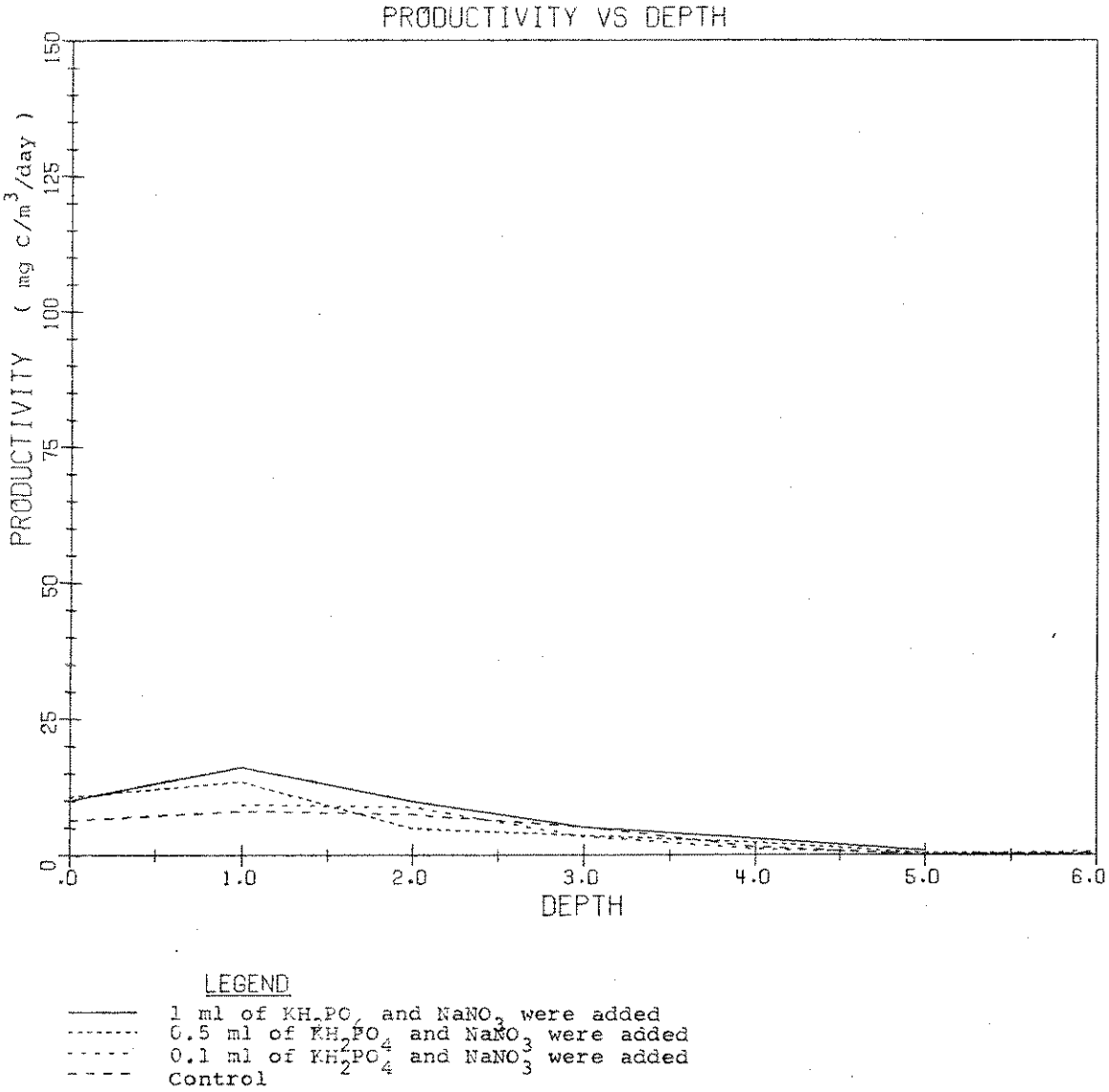


Figure 13 Response of phytoplankton growth to phosphate and nitrate enrichment in in situ bioassay cultures as measured by carbon-14 assimilation on May 26, 1975 in Lake Monroe, Indiana.

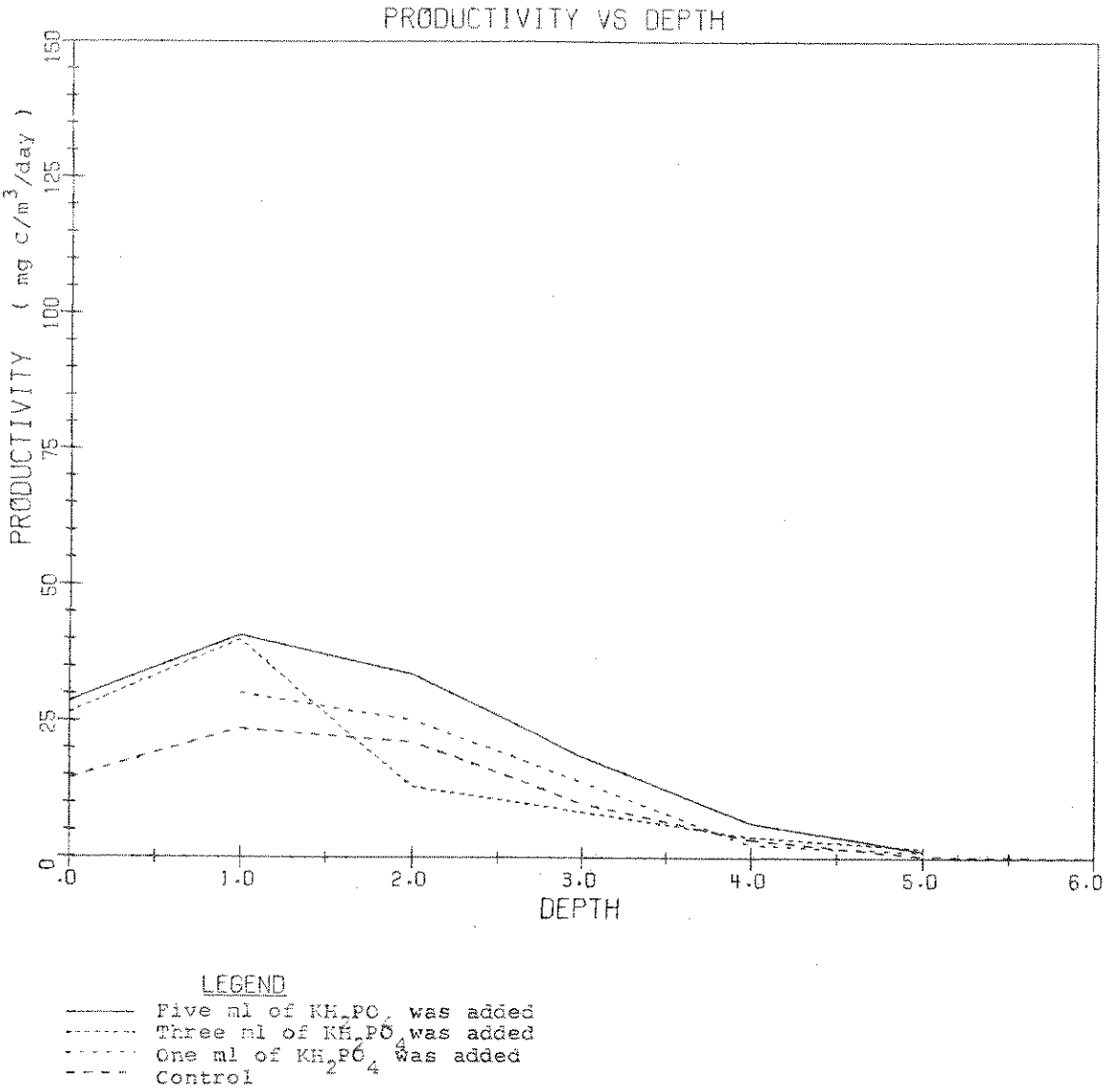


Figure 14 Response of phytoplankton growth to phosphate enrichment in in situ bioassay cultures as measured by carbon-14 assimilation on October 27, 1975 in lake Monroe, Indiana.

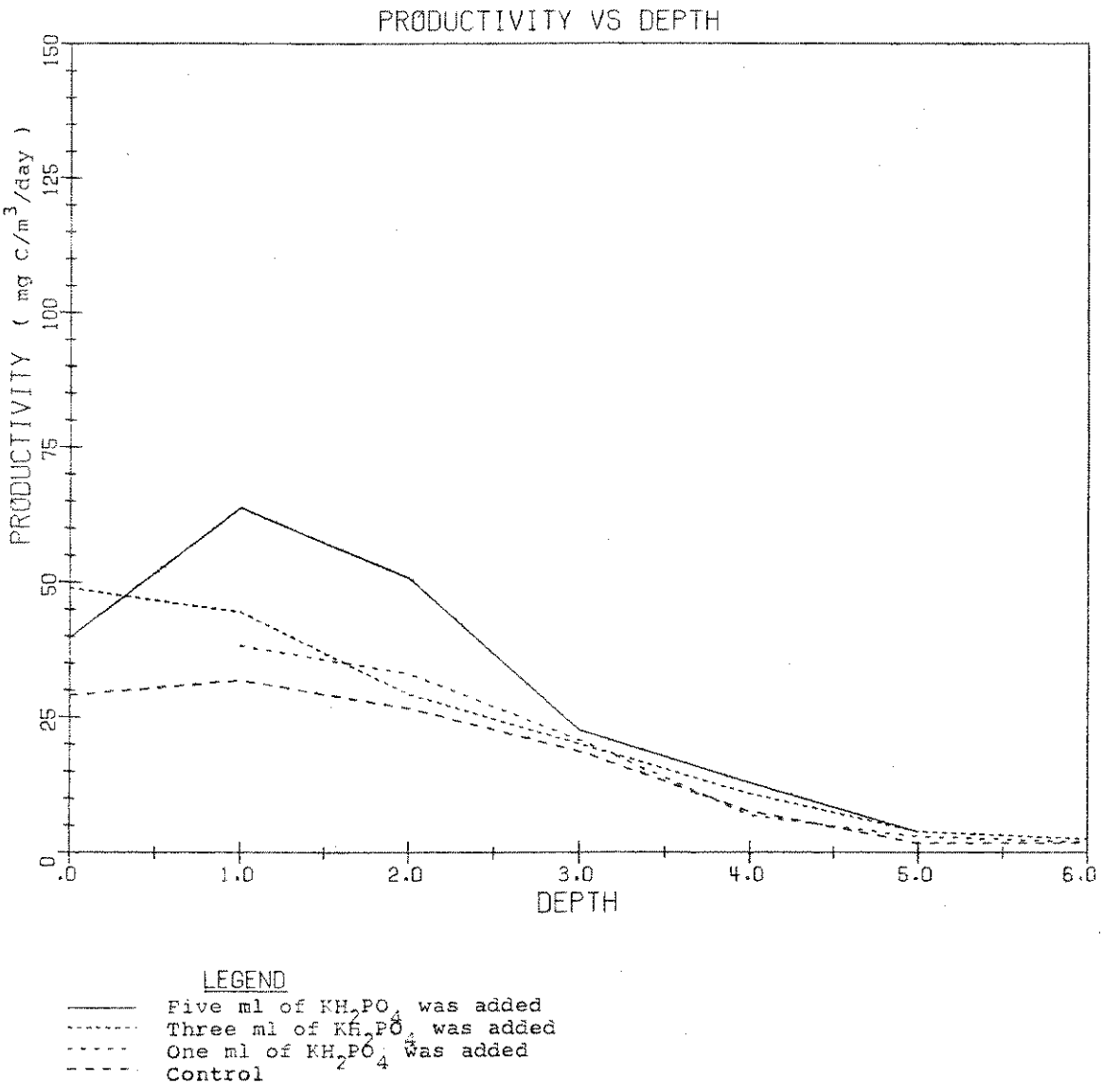


Figure 15 Response of phytoplankton growth to phosphate enrichment in <u>in situ</u> bioassay cultures as measured by carbon-14 assimilation on April 7, 1976 in lake Monroe, Indiana.

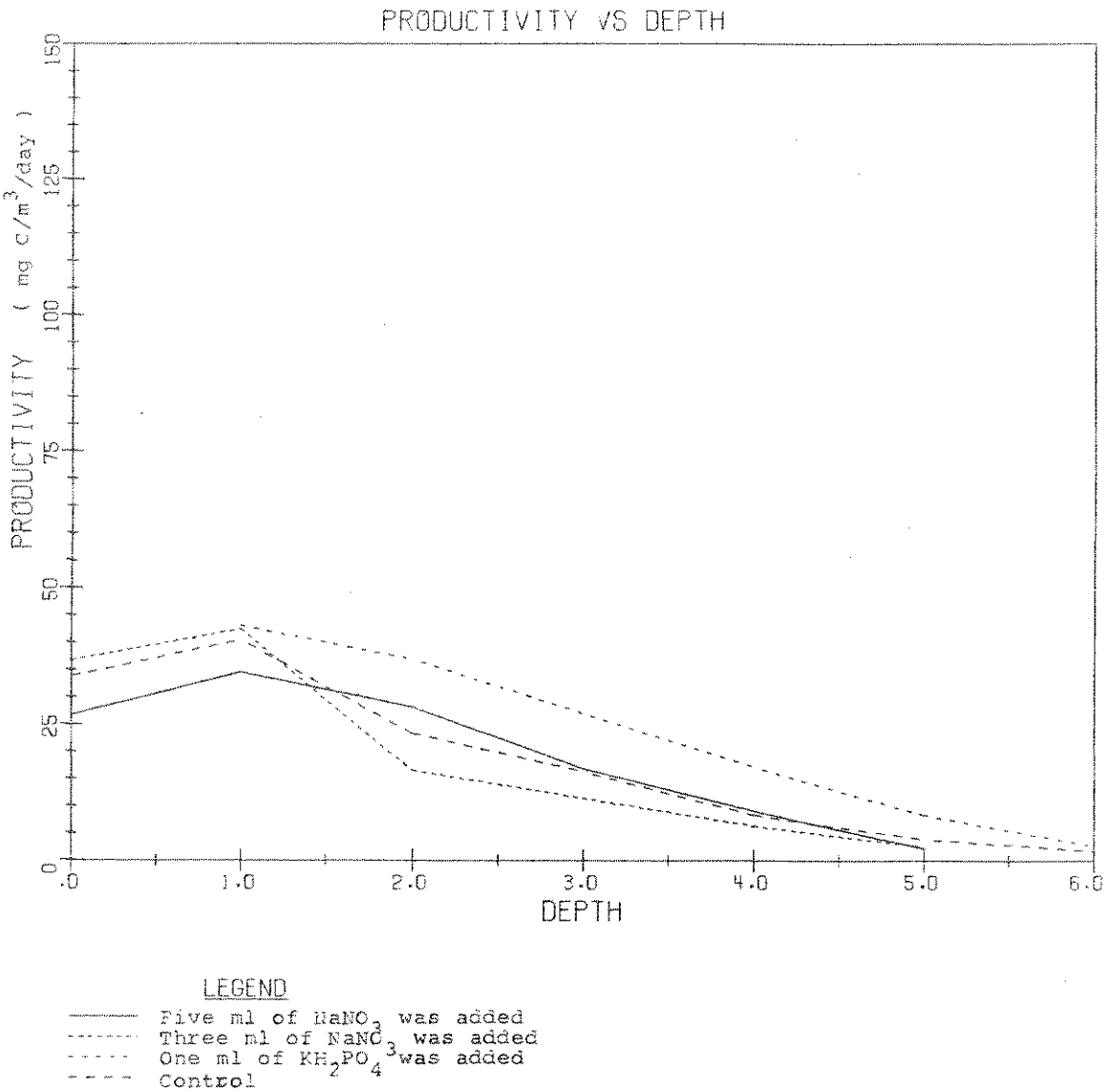


Figure 16 The comparison of the response in phytoplankton growth between phosphate enrichment and nitrate enrichment in <u>in situ</u> bioassay cultures as measured by carbon-14 assimilation on April 21, 1976 in lake Monroe, Indiana.

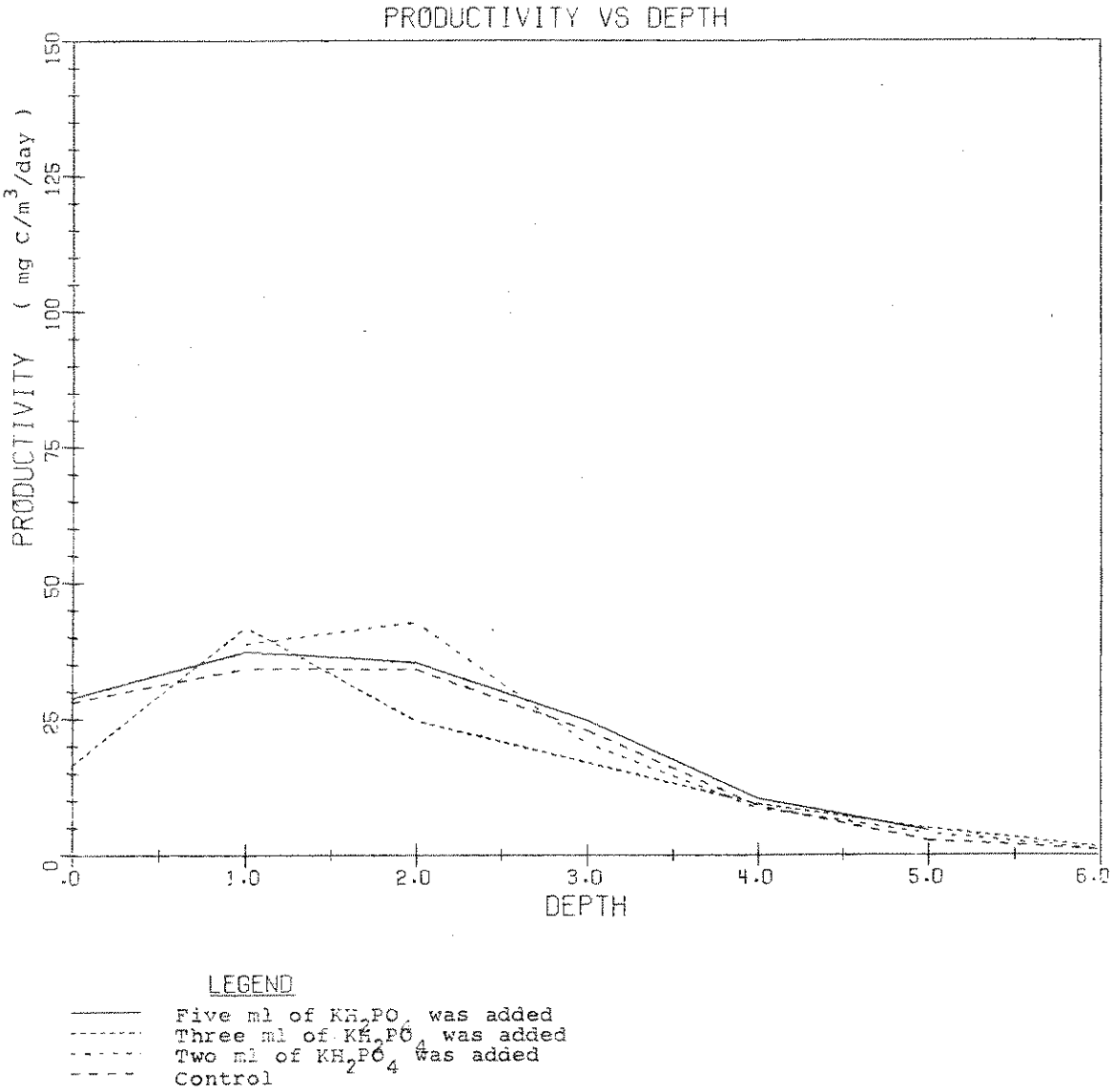


Figure 17 Response of phytoplankton growth to phosphate enrichment in <u>in situ</u> bioassay cultures as measured by carbon-14 assimilation on May 24, 1976 in lake Monroe, Indiana.

TABLE 2. Response of Phytoplankton Growth to Nutrient Enrichment in in situ Bottles, as Measured by C-14 Uptake, Lake Monroe, Indiana.

Date	Nutrient added KH_2PO_4	Nutrient added $NaNO_3$	Significance of response* (*at 5% level) (**at 1% level)	Photoinhibition
1975				
May 5	x		*	+
12		x		
15	x	x		
19	x		**	+
22		x		
26	x	x	*	+
June 9 (06:30)	x	x		
9 (10:30)	x	x		
9 (14:30)	x	x		
July 16	x			
23		x		
30	x			+
Aug. 3		x		
13	x			
18		x		
Sept. 1	x			
15		x		
29	x			
Oct. 13		x		+
27	x		**	+
Nov. 24		x		
Dec. 8	x			
1976				
Feb. 8		x		
Mar. 3	x			
19		x		+
Apr. 7	x		**	+
21	Set A	Sets B,C	**(A)	+
May 24	x		**	+
June 7	x			+
24		x		
July 6	x			+
20		x		+
Aug. 3	x			+
16	x			+

TABLE 3. Comparison matrices of the response of phytoplankton to incremental additions of nutrients, using Fisher's distribution-free sign test. Only those experiments that gave significant responses are included.

Date	Nutrient		Nutrient Treatment A	B	C
1975					
May 5	KH_2PO_4		1 ml	2 ml	3 ml
		Control	-	T	+
		A (1 ml)		-	T
		B (2 ml)			+
May 19	KH_2PO_4		1 ml	2 ml	3 ml
		Control	-	-	++
		A (1 ml)		-	+
		B (2 ml)			+
May 26	KH_2PO_4		.3 ml	.5 ml	1 ml
	+	Control	T	T	+
	$Na\ NO_3$	A (.3 ml)		-	+
		B (.5 ml)			T
Oct. 27	KH_2PO_4		1 ml	3 ml	5 ml
		Control	T	T	++
		A (1 ml)		-	+
		B (3 ml)			+
1976					
Apr. 7	KH_2PO_4		1 ml	3 ml	5 ml
		Control	+	++	++
		A (1 ml)		T	++
		B (3 ml)			T
April 21	KH_2PO_4		1 ml	3 ml	5 ml
	A	Control	++	-	-
	$NaNO_3$ in	A (1 ml)		-	-
	B&C	B (3 ml)	+		-
		C (5 ml)	+	-	
May 24	KH_2PO_4		1 ml	3 ml	5 ml
		Control	T	T	++
		A (1 ml)		T	-
		B (3 ml)			-

++ = significant at 1% level
+ = significant at 5% level
T = productivity increased but not significant
- = no difference in response

and 5 ml of N to another two sets, productivity was stimulated only by the addition of phosphate (Table 4; Fig. 16). Moreover, in the autumn of 1975, a species of blue-green alga (Anabaena) appeared, which is capable of fixing elemental nitrogen to a usable form. This would further reduce any limitation by nitrogen on phytoplankton growth. All these lines of evidence indicate that phosphorus rather than nitrogen limits the growth of phytoplankton in Lake Monroe.

TABLE 4. Concentrations of stock solutions used in the micronutrient experiments. These are the same concentrations used in the EPA Algal Assay Procedure, Bottle Test (1971). In the field 0.2 ml of a particular nutrient was transferred to a 125-ml bottle, resulting in per-liter concentrations 1.6 times the values in this table.

Chemical	Concentration per ml
$MgCl_2 \cdot 7\ H_2O$	12.16 mg
$MgSO_4 \cdot 2\ H_2O$	14.70
$CaCl_2 \cdot 2\ H_2O$	4.41
$NaHCO_3$	15.00
H_3BO_3	185.52 µg
$MnCl_2$	264.26
$ZnCl_2$	32.71
$CoCl_2$	0.78
$NaMoO_4 \cdot 2\ H_2O$	7.26
$FeCl_3$	96.00
$Na_2EDTA \cdot 2\ H_2O$	300.00

MICRONUTRIENT

The importance of micronutrients in the growth of algae has been recognized for many years, but in situ research has just recently begun, most investigators having concentrated their effort on the major nutrient requirements of the planktonic algae. Recently several investigators, including Nicholas (1963), Wetzel (1965, 1966a, 1971), and Goldman (1969), have become interested in the micronutrients.

The micronutrient analysis in this study used methods similar to those for the macronutrients already described. This in situ uptake of C-14 is advantageous because it is extremely sensitive, it does not require the time necessary for cell division, and hence it can be accomplished before significant changes in population density and diversity occur.

On June 28 and July 2, 7, and 9, the effect of micronutrients in stimulating photosynthesis was measured (Table 4). The micronutrients were added singly, or in pairs ($MgCl_2$ + $MgSO_4$; $MgCl_2$ + $CaCl_2$; Na_2MoO_4 + H_3BO_3), or as a group ($ZnCl_2$, $CoCl_2$, $MnCl_2$, $FeCl_3$). A total of 92 bottles was tested. The only significant increases resulted from the addition of EDTA. On July 2 photosynthesis in the EDTA treatment was 81.5% greater than the control, which was significant at the 1% level (Fisher distribution-free sign test). On July 9 the increase was 42.8% over the control, which was significant at the 5% level.

Similar results have been obtained by other investigators on other lakes. Goldman (1972) reported that iron chelated with EDTA

was very stimulatory in Lake Coleridge and two other lakes in New Zealand. Allen (1972) studied Star Lake, a soft water lake in Vermont. The addition of 1.0 mg EDTA/l produced a 30% increase in growth over the controls. When 16 µg Fe/l was added along with the EDTA, an increase in growth of 115% over the controls in only 3.5 hours was obtained. Wetzel (1972) worked with a series of marl lakes in northeastern Indiana, particularly Crooked Lake and Little Crooked Lake. In chemical composition and trophic level the two lakes are significantly different. Little Crooked Lake has higher concentration of Fe, P, N, trace elements, and dissolved organic matter than Crooked Lake (Wetzel, 1966b). Little Crooked Lake is considered to be a eutrophic lake, while Crooked Lake is only a moderately mesotrophic lake. Wetzel observed that in Crooked Lake the addition of iron alone stimulated growth. The response was doubled if EDTA was added simultaneously. EDTA by itself increased growth 40 - 140% over the controls. In Little Crooked Lake the growth responses to iron were considerably less than in Crooked Lake and often negligible. The addition of EDTA in combination with iron gave no additional growth in Little Crooked Lake. The summary of these findings is given in Table 5.

Na_2EDTA affects algal nutrition by its chelatory capacities for metals and cations. The chelation generally brings an equilibrium reaction between a metal or cation and a chelating agent, resulting in the formation of a stable structure incorporating the metal ion, or in the formation of a strong ion-bond with the cation. Furthermore, the chelation can function in many complex ways in accordance with the

environmental conditions and the concentration of chelator and cations. For example, when concentrations of 1000 and 100 µg EDTA/l were added to prefiltered Lawrence Lake water containing 100 µg Fe/l the structure of the iron compounds increased in complexity and size, most of them being larger than 0.22 µm in size. A lower concentration of EDTA resulted in a greater proportion of the iron compounds less than 0.22 µm in size and an increase in the availability of iron (Fig. 18, based on data in Wetzel, 1972).

TABLE 5. Stimulation of primary production in various lakes by the addition of EDTA singly or in combination with iron. Data for Lake Monroe are from this study. Data for the other lakes are from Wetzel (1967), Allen (1972), and Goldman (1972).

Lake	Hardness	Amount of organic matter	Production stimulated by Na_2EDTA	Fe + Na_2EDTA
Star	soft	poor	20-29	100-109
Monroe	soft	poor	40-89	---
Goose	hard		---	10-19
Little Crooked	hard	rich	---	0-9
Crooked	hard	poor	130-139	10-19
Coleridge			---	30-39
Pearson			---	1-19

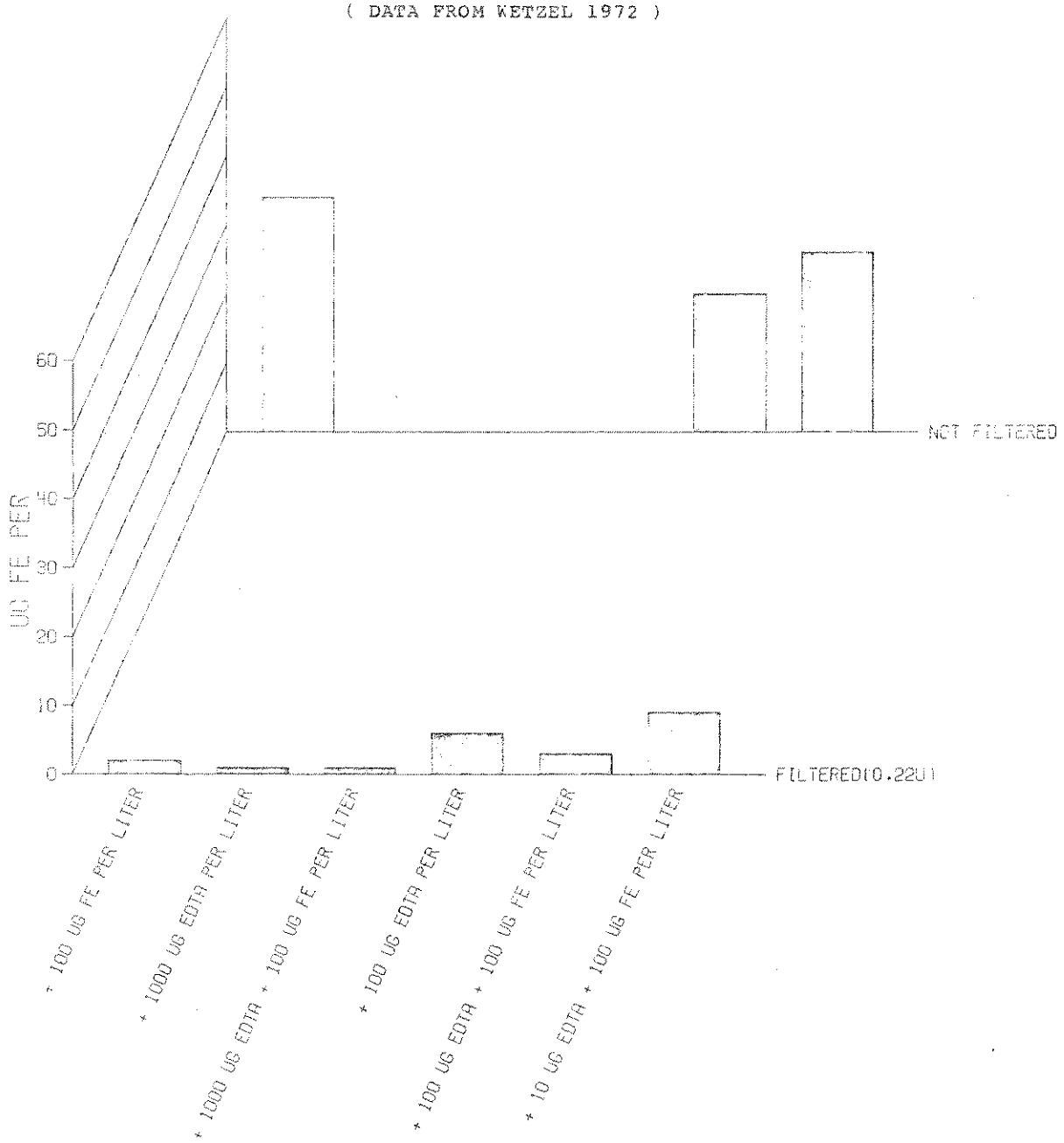
--- indicates not measured

The effect of EDTA in a heterogeneous solution such as lake water, like most other chelators, is governed by environmental condition of ionic strength of various anions, the composition and amount of organic materials, the ratios of chelators to ions (cations or metals), and the stability constants of chelates for different ions within the active series.

Figure 18 EFFECT OF EDTA (OF NA SALT) ON SOLUBILITY OF FE

ALL SAMPLES PREFILTERED 0.45U
WATER FROM LAWRENCE LAKE

(DATA FROM WETZEL 1972)



The function of EDTA and other chelators in lakes is not only to chelate the metal ion, which keeps the metal-ion from precipitating out of the euphotic zone, but also to increase the availability of physiologically essential ions. For instance, EDTA can successfully compete for cations, such as the Ca of $Ca_3(PO_4)_2$, thereby releasing phosphate for utilization. But the effects of EDTA are greatly weakened if greater concentrations of natural organic matter are already functioning in a chelation capacity. This apparently happened in the case of Little Crooked Lake when the addition of EDTA had no additional effect on growth (Wetzel, 1966b). In the case of Star Lake the organic matter in the water was not very abundant, even though the lake is eutrophic. EDTA thus had a significant effect. As to Lake Monroe, it is a moderately productive, slightly alkaline man-made lake with low total ionic content and low dissolved organic matter. Consequently, EDTA would be expected to have a significant effect.

Little is known about utilization of EDTA in algae, and therefore EDTA cannot be regarded as a limiting micronutrient. Because the research on micronutrients failed to disclose any that are limiting production significantly, our belief is strengthened that phosphorus is the major, and perhaps the sole, factor limiting algal growth in Lake Monroe.

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